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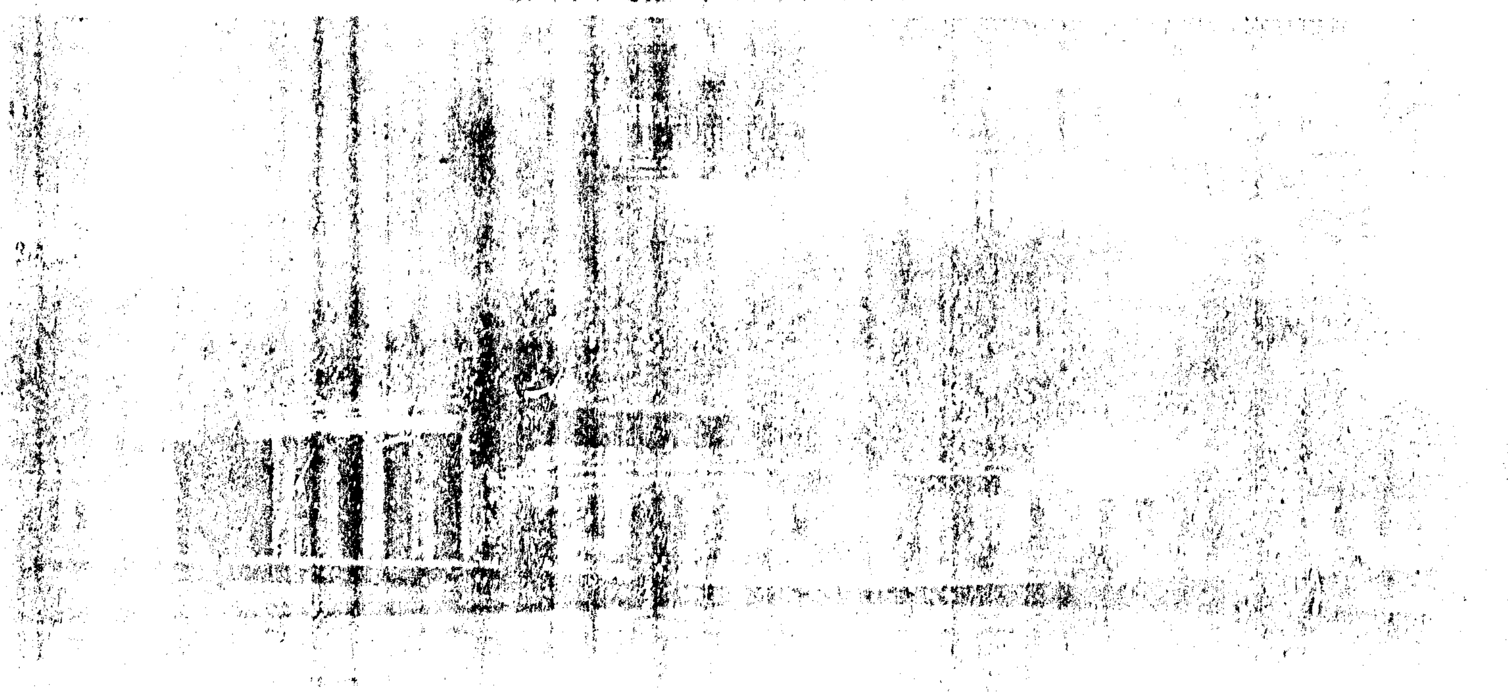
Report [illegible]

RESPONSE OF TWO [illegible] SOILS TO VARIOUS ST[illegible]

S. R. Macor[illegible]



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[illegible] Contract No. [illegible] 9051

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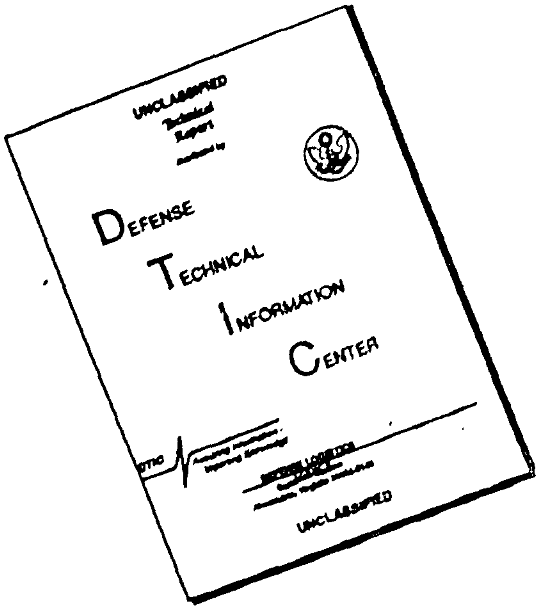

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CONTRACT REPORT S-70-2

STUDY OF SOIL BEHAVIOR UNDER HIGH PRESSURE

Report 1, Volume I

RESPONSE OF TWO RECOMPACTED SOILS TO VARIOUS STATES OF STRESS

by

B. B. Mazanti, C. N. Holland

February 1970

Sponsored by Defense Atomic Support Agency

Conducted for U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Under Contract No. DACA 39-67-C-0051

By Georgia Institute of Technology, Atlanta, Georgia

ARMY-MRC VICKSBURG, MISS

FOREWORD

This report presents the results of a research project conducted by the Georgia Institute of Technology, Atlanta, Georgia, under the direction of Dr. B. B. Mazanti, Associate Professor of Civil Engineering. Mr. J. H. Holland served as Associate Director of the project.

There are three separate volumes documenting this project. Volume I describes the development of equipment and test procedures, soil analysis and specimen preparation, and analysis of results. Volume II contains the basic results of all tests conducted for this program in the form of stress-strain plots. Volume III contains the numerical tabulation of test data in the form of computer sheet printout. Only a limited number of copies of the Volumes II and III were published; however, interested readers may borrow a copy on 30-day loan from the Research Center Library, Waterways Experiment Station.

The Georgia Institute of Technology has been engaged in research concerned with the effects of high pressure on soil and rock for approximately ten years. During this time period, a considerable amount of equipment and instrumentation has been developed for high pressure testing, financed almost entirely by Georgia Tech. Much of the equipment and instrumentation utilized in the performance of this research was of such origin.

This report was requested and authorized by Mr. J. G. Jackson, Jr., Impulse Loads Section, Soil Dynamics Branch, under the direction of Messrs. W. J. Turnbull and A. A. Maxwell, Chief and Assistant Chief, respectively, Waterways Experiment Station Soils Division. The work was part of Contract No. DACA 39-67-C-0051, Project B-602, and was conducted for the U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi, under Defense Atomic Support Agency sponsorship, during the period November 1967 through November 1968.

Directors of the Waterways Experiment Station during the performance of this work and preparation and publication of this report were COL John R. Oswalt, Jr., CE, and COL Levi A. Brown, CE. Technical Directors were Messrs. J. B. Tiffany and F. R. Brown.

CONTENTS

VOLUME III

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
pounds per square inch	0.070307	kilograms per square centimeter
pounds per cubic foot	16.0185	kilograms per cubic meter
pounds	0.45359	kilograms

LIST OF SYMBOLS

p	Hydrostatic Pressure
σ	Normal Stress
σ_1	Major Principal Stress
σ_2	Intermediate Principal Stress
σ_3	Minor Principal Stress
σ_a	Axial Stress
σ_r	Radial Stress
τ	Shear Stress
ϵ	Strain
ϵ_a	Axial Strain
ϵ_r	Radial Strain
ΔV	Volume Change
V_o	Original Volume
$\Delta V/V_o$	Volumetric Strain
K^o	Condition of No-Lateral-Strain
C	Mohr Shear Intercept
ϕ	Mohr Friction Angle

LIST OF ILLUSTRATIONS

SUMMARY

This report, Volume I, is concerned with the load-deformation characteristics of two field soils under confining pressures up to 10,000 psi. A wide variety of stress states were imposed upon partially saturated compacted specimens of soil which were obtained from two test sites, one in the United States and the other in Canada. The tests were performed with a high-pressure triaxial cell and the stress states included hydrostatic compression, triaxial shear, constant stress ratio tests, and no-lateral-strain tests. Cyclic loading was accomplished during many of the tests. Results of tests are presented in the form of various types of stress-strain curves in Volume II. Numerical tabulation of data is presented in Volume III.*

A lateral deformeter was developed for determining lateral deformations of the cylindrical soil specimens during both the compression and the shear stages of loading. The instrument consists basically of strain-gaged, cantilevered springs which bear against the specimen midheight. The use of the instrument allowed the determination of the bulk modulus of the partially saturated soils as well as the control over the lateral dimensions of the specimens during the loading.

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* Volumes II and III were published in a limited number and are available for loan purposes from the Research Center Library, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

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The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

CHAPTER I

INTRODUCTION - SCOPE OF PROJECT

In order to determine the free-field behavior of soils as well as soil-structure interaction behavior under blast loadings, it is necessary to have knowledge of the dynamic, high-confining-stress level, stress-strain characteristics of the soil. At the present time there is a complete lack of test equipment for performing high-pressure, dynamic triaxial tests. There is available, however, dynamic triaxial equipment capable of operating at low-confining pressures and, also, dynamic one-dimensional compression devices operable at loading pressures in the 1000- to 2000-psi range. One solution, then, to the basic high-pressure, dynamic loading problem is to correlate static-loading triaxial data with the dynamic data in the range of pressures where both types of data are available. The correlations could then be extrapolated to the high-pressure dynamic problems on the basis of high-pressure static tests.

A survey of the literature reveals that very little data are available even for static loading of soils in the pressure range of interest. This is particularly true for controlled states of stress during both loading and unloading other than "standard" triaxial test conditions. As a consequence of the lack of data, this project was initiated in order to study the behavior of two test-site soils when subjected to high confining pressures. Of primary interest were the stress-strain characteristics at relatively low strain conditions in order to determine deformational and bulk moduli.

Material properties of interest include the bulk modulus of compressibility, the shear modulus, and the constrained modulus. The determination of these quantities involves a measurement of lateral deformations of cylindrical specimens. At the inception of this contract, there was no instrumentation available for such measurements under the pressure conditions required. The development of a reliable apparatus for this use would provide an invaluable tool which would, in addition, allow testing under stress states not then possible.

The scope of work in the project included the following three studies:

1. Triaxial testing of compacted soils at confining pressures up to 10,000 psi.
2. The development and use of an instrument with which to measure lateral (radial) displacements of soil specimens subjected to high pressure.
3. Triaxial testing of undisturbed soil specimens at confining p[illegible] up to 10,000 psi. This study was to [illegible]orted in separate letter-type reports as th[illegible]k was accomplished and, therefore, is not covered in this report.

Two soils were included in the test program for compacted soils. One was an alluvial clayey sand from the McCormick Ranch test site near Albuquerque, New Mexico, and the other was a silty clay from the lacustrine deposits of the Watching Hill test site at the Defence Research Establishment, Suffield, Canada. Both soils were furnished by WES in a loose state after having been dried and processed to remove large particles and foreign matter such as twigs, etc.

CHAPTER II

EXPERIMENTAL APPARATUS AND CALIBRATION

With the exception of the triaxial cell, the pressure generating system and the lateral deformeter, the equipment comprised commercial items. The lateral deformeter design is included in Chapter III. Description of the other equipment is included here.

Equipment

Triaxial Cell

The triaxial cell (Figure 1) was designed to allow the testing of specimens up to 2 inches in diameter and with lengths up to 5 inches. The working pressure capacity of the cell is 10,000 psi. It consists of four basic parts. These are: (1) the base, (2) the cylinder, (3) the gland, and (4) the load piston.

The base was machined from naval brass with a tensile yield strength of approximately 24,000 psi. The base diameter is 8 inches with a threaded pedestal $3\frac{1}{2}$ inches in diameter. A removable specimen pedestal (or platen) screws into the base pedestal. Two pressure ports are provided through the base. One port is for the confining pressure while the second allows either the application of a pore pressure, the measurement of pore pressures, or drainage of the specimens.

The cylinder is of cold-drawn seamless steel tubing with a yield strength of about 55,000 psi. It screws to the base and is sealed by an O-ring seal between the pedestal and the cylinder. The internal diameter is $3\frac{1}{2}$ inches, the wall thickness is 13/16 inch, and the length is 12-13/16 inches. Two ports were provided in the cylinder wall. One was used as either a pressure port or as an air escape port when filling the chamber with oil. The other port allowed the attachment of an electrical-lead manifold. The electrical terminals are manufactured by the Fusite Corporation, Cincinnati, Ohio, and consist of a fused glass insulation material surrounding the terminal and contained in a metal body. They are available in several types and sizes. The type used in this application was a 1/8-inch pipe-thread body.

The gland screws into the top of the cylinder and serves as a guide for the piston. It is made of naval brass. Sealing is accomplished by means of an O-ring between the gland and the cylinder as well as between the gland and the piston. Although three O-ring grooves were provided for sealing the piston, it has been found satisfactory to use only one. A different gland was used for each of the two piston sizes.

The pistons are of alloy steel with a yield strength of approximately 150,000 psi. The diameters were 7/8 inch and 1.40 inches and polished.

Pressure Generating System

The pressure generating and regulating system is shown schematically

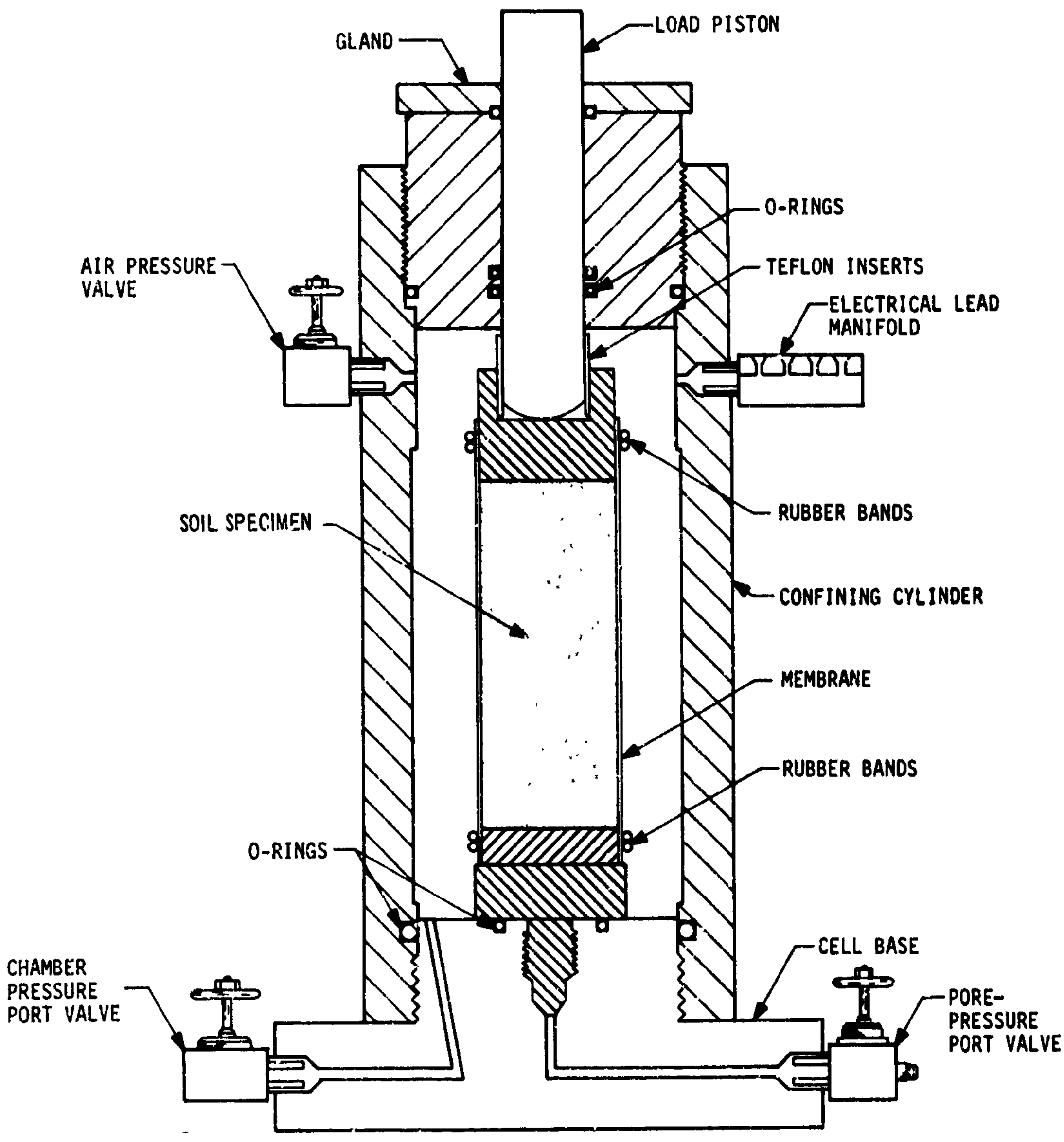


Figure 1. Triaxial Cell

in Figure 2. An air-operated hydraulic pump is used as the prime pressure source. The pump is essentially a pressure intensifier which is valved so that it is capable of recycling when the stroke limit is reached. The pump used is made by SC Hydraulic Corporation, Los Angeles, California.

It is a Model 10-600-15 and has a fluid pressure capacity of 23,700 psi when operating at air pressure of 100 psi. The output pressure depends upon the applied air pressure and is continuously variable (increasing pressure only) from approximately zero. The major disadvantage of the pump is that it can "unload" only a negligible amount.

In order to accurately control the confining pressure, there is included in the line a piston-cylinder arrangement (Figure 3). The pistons are positioned by a bolt reaction member. The adjustment of the bolt either forces the piston into the cylinder or allows it to move outward, thus causing the pressure in the line to increase or decrease, respectively.

In certain tests, particularly the No-Lateral-Strain or K^o, it was necessary to rapidly adjust the confining pressure. In those cases, a manually operated, 10,000-psi hydraulic pump was utilized.

Loading Machine

The loading machine is of the "constant rate of strain" type. It is a 10-kip capacity, electrically operated machine with selectable strain rates ranging from 0.30 inch per minute to 0.000024 inch per minute. It is manufactured by Wykeham Farrance Engineering Ltd., Slough, England.

Measurement System

Lateral Deformeter

The lateral deformeter was specially designed for the project and consisted basically of a cantilever-spring system which utilized bonded-wire, resistance-type strain gages as the sensing elements. A complete description of this device is included in Chapter III.

Pressure Gages

Confining pressures were measured by means of commercial pressure gages. The following set of gages was used:

Pressure Range	Accuracy, %, Full Scale (F.S.)
0-200 psi	± 0.5
0-400 psi	± 0.5
0-1,000 psi	± 0.5
0-20,000 psi	± 0.1

The gages were periodically checked against a standard transfer gage

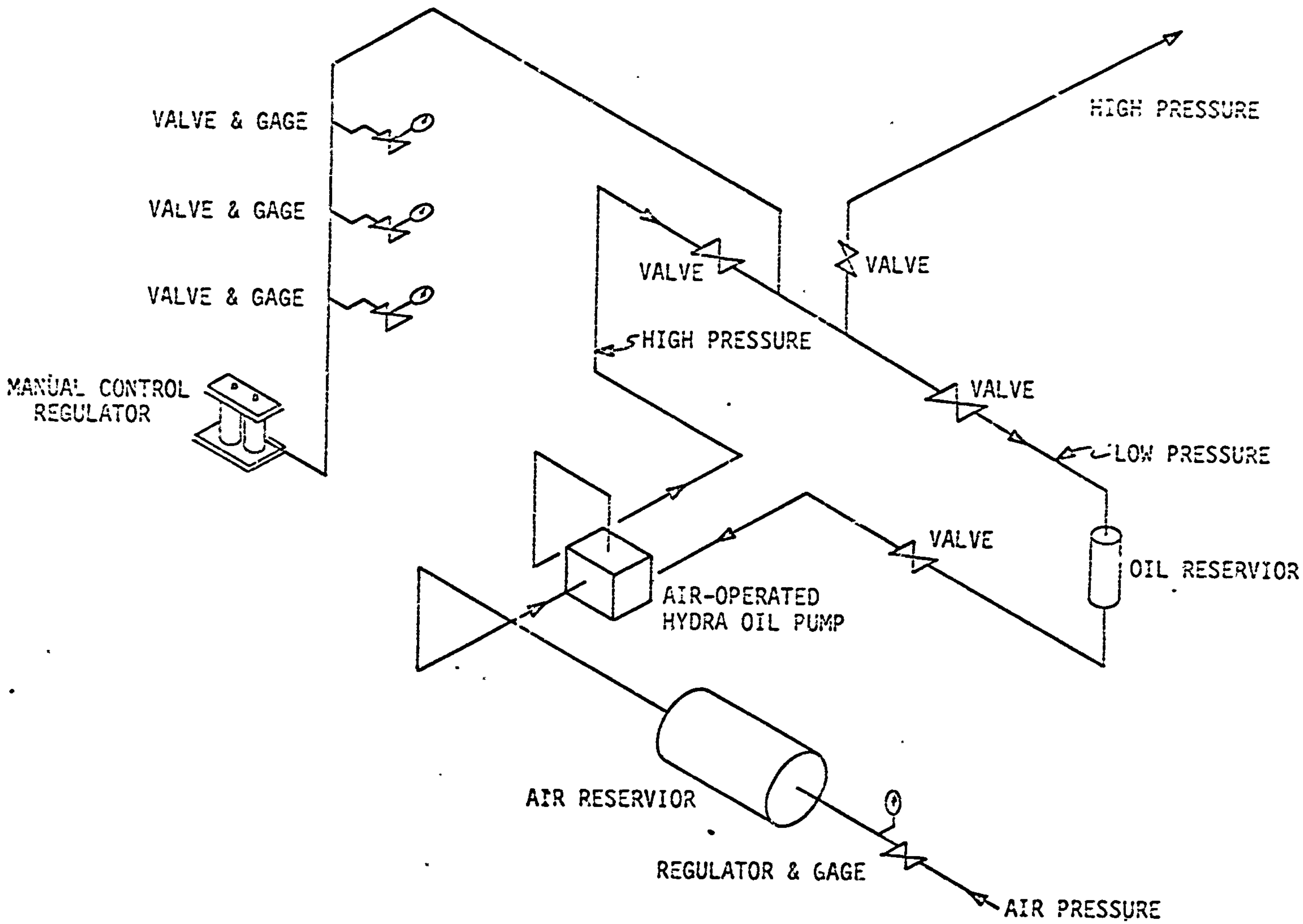


Figure 2. Pressure Generating and Regulating System

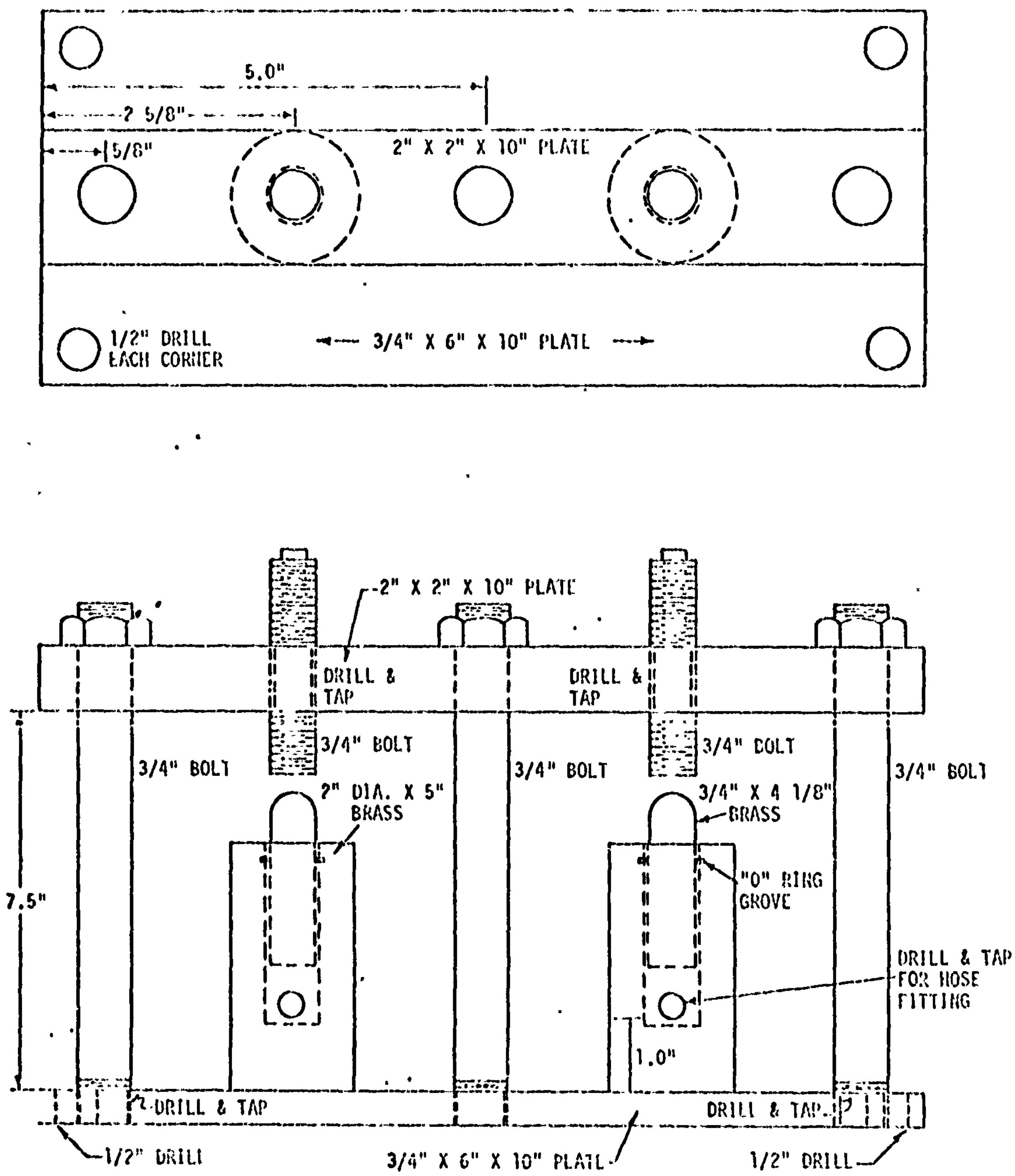


Figure 3. Manual Control Regulator

accurate to ± 0.1% F.S. The standard gage was calibrated with a precision, 20,000-psi dead-load tester.

Load Cells

Three different load cells were used to measure axial loads on the specimens. All were commercial load cells of the bonded-wire, electric resistance type. For loads up to 2.5 kips a Strainsert flat load cell was used. This cell has a nominal diameter of 2-1/4 inches and a thickness of 3/4 inch. Nonlinearity of the cell is within ± 0.10% F.S. and repeatability is ± 0.0[illegible]% F.S.

For loads up to 10 kips, a BLH load cell was used. The cell is approximately 4 inches in diameter by 6 inches in length. Linearity and repeatability are equivalent to that shown for the 2.5-kip load cell.

For loads up to 25 kips, a Strainsert flat load cell was used. The cell is 4-1/8 inches in diameter by 1-3/8 inches thick. Linearity and repeatability are as indicated for the 2.5-kip cell.

Linear Motion Transducers

Linear motion transducers (LMT's) were used for the measurement of axial deformations of the specimens. The devices are linear variable differential transformers (LVDT's) which are completely self-contained with respect to the signal carrier and amplification system. The devices are excited by an external 24 v. D.C. source and the output signal is sufficiently strong to go directly to a recorder.

The LMT's used were made by G. L. Collins Corporation, Model SS207 with a stroke length of ± 1.00 inch. Linearity for these instruments is 0.[illegible]

Recording and Instrumentation

Strain Gage Indicator

All strain gage circuits were fed into a BLH Model 120C strain gage indicator. Those signals being recorded were retransmitted through the scope output to the recorder.

X-Y Recorder

A Hewlett-Packard Model 135 Recorder was used for all automatic recording. This is a multirange, general purpose X-Y plotter with ranges from 0.5 mv/inch to 50 v/inch. Accuracy is 0.2% F.S. and linearity 0.1% F.S.

Circuitry for Linear Motion Transducers

The LMT's were used in an averaging arrangement. This is accomplished by mounting two LMT's to the testing machine at 180 degrees around the cell. The output from the two units was added by connecting all output

load wires in a series combination. The circuitry for the setup is shown in Figure 4.

Calibration

Load Cells

All load cells were calibrated in place on the testing maching. Proving rings, which had been calibrated immediately prior to their use, were used to monitor the applied loads. The output from the load cells was retransmitted from the strain gage indicator to the recorder. Each recorder range was utilized during th. calibration process so that changing of recorder ranges was possible during the testing process. For a given recorder range, the relation between load and recorder indication was linear.

Calibration of load cells was accomplished at the time of installation and every two weeks thereafter while a given cell was in use. For service periods less then two weeks, the cell was checked prior to its removal from the testing machine.

Linear Motion Transducers

The transducers were calibrated in position on the testing machine. They were set at the null position and then subjected to known deflections (individually and together). The output from transducers was transmitted directly to the recorder and all recorder ranges to be used were checked. The relation between deflection and recorder indication was linear in all cases.

The transducers were calibrated prior to their use and every two weeks thereafter.

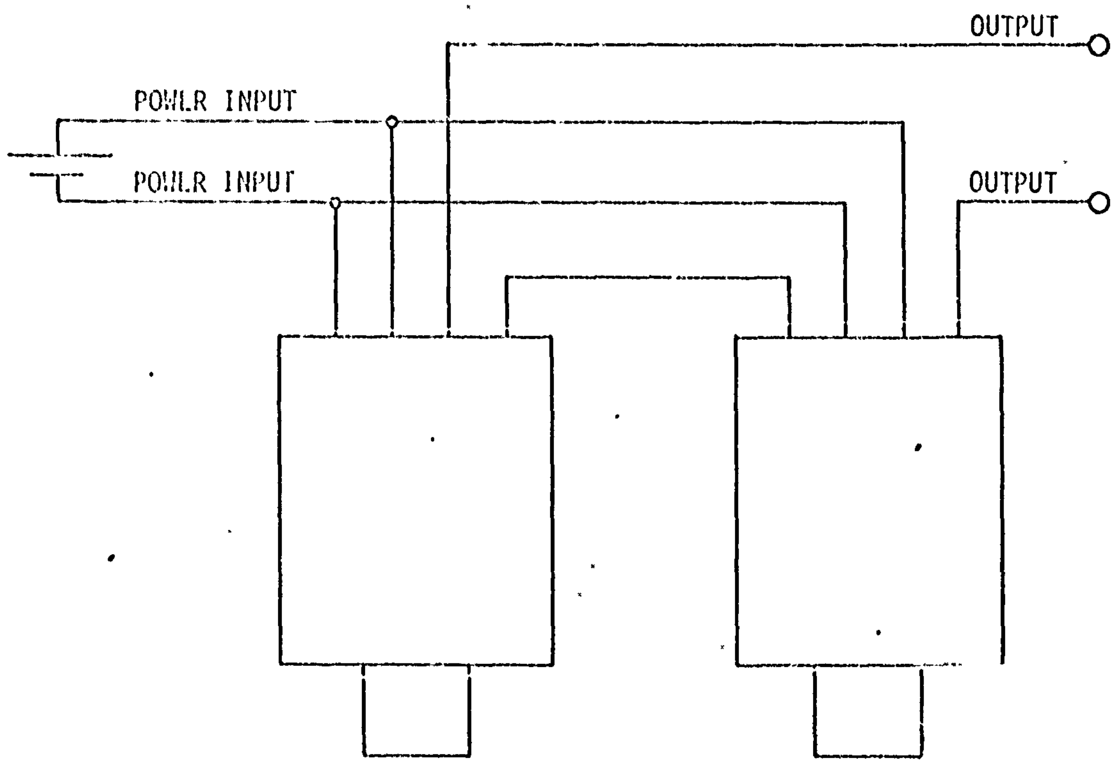
Testing Machine Deflection

Since the axial deformation measuring system was mounted so as to include in the measurements the deflection of the testing machine, load cell and the triaxial cell, the combined effect of the equipment deformations was determined.

A steel specimen was placed in the triaxial cell and the equipment completely assembled as for an actual test. Loads were applied to the dummy specimen under all confining pressure conditions which were anticipated and the total deflection was recorded. The deformation of the metal specimen was calculated and this amount of deformation was subtracted from the actual measurements. The remaining deflection was recorded as the equipment deflection and was utilized as deformation correction factors in the reduction of data.

Piston Friction

Since the specimen loads in the axial direction were measured by means of a load cell mounted outside of the confining chamber, the piston



MULTIPLE AVERAGING DUAL UNIT

Figure 4. Wiring Diagram for Vertical Displacement Transducers

friction was determined at pressures from zero up to 10,000 psi. The appropriate correction was then applied to the measured loads during calculations of axial stress on the specimens.

CHAPTER III

DEVELOPMENT OF THE LATERAL DEFORMETER

Triaxial testing of both partially saturated and fully saturated soils under unconsolidated-undrained conditions to determine bulk, shear, and constrained moduli is difficult to accomplish.

In the case of bulk modulus tests, the overall volume change of the specimen is of interest and this determination may be accomplished by either observing changes in volume of the confining medium or by measuring both axial and radial deformations of the specimens. For the constrained modulus test, it is mandatory that radial deformations be monitored in order to maintain conditions of "no lateral strain." To determine the shear modulus, it is also necessary to detect radial deformations.

The accurate measurement of very small volume changes of triaxial specimens by observing changes in confining fluid volume becomes difficult under high pressure conditions. This is due to volume changes of the equipment and the confining medium themselves as well as the introduction of measurement errors due to small leaks in the system. Although precise calibration may provide a basis for corrections due to equipment and confining-medium volume changes, the problem of system leakage is formidable in a production-oriented test system. This indicates the desirability of obtaining deformation measurements in the radial and the axial directions during the progress of a test. Relatively precise measurements of axial deformations are possible using instruments such as linear variable differential transformers. This type of instrumentation was used in this project. The problem of determining lateral deformations of soil specimens at high confining pressures is much more difficult and, prior to this investigation, has received little attention.

The scope of the project included a study of the feasibility of developing the necessary equipment to conduct meaningful unconsolidated-undrained bulk, shear, and constrained modulus tests. Such equipment has been developed during the progress of the project and it has been used in the conduction of the type of tests anticipated. The development and usage of the "lateral deformeter" constitutes the remainder of this portion of the report.

Lateral Deformation Measurement Techniques

In low-pressure triaxial testing, various techniques have been investigated and used. The more widely publicized of these may be conveniently listed as follows:

1. Shadowgraph methods are those wherein diameter changes are indicated by changes in lateral dimensions of a shadow of the specimen. A variation of this method is cited by Marsal et al (1).

Marsal utilized (or suggested the use of) a photographic plate together with a parallel-light source in order to record lateral dimension changes.

2. Visual observations of diameter changes are possible with the use of a calibrated scale mounted on the triaxial cell wall (2).

3. Manual, direct measurements of diameter changes can be made by using mechanical micrometer gages which extend through the triaxial cell wall (3).

4. Capacitance gage methods which utilize one plate of a capacitor mounted to the specimen side and the other plate attached to the cell. Changes in capacitance of the measuring system occur as the specimen deforms which decreases (or increases) the spacing between the two plates.

5. Mechanical lever systems have employed plates bearing against the specimen sides. The plates cause movement of the levers as the specimen diameter either decreases or increases and the resulting deformation is indicated by some scale arrangement. Bishop and Henkel (5) utilize a calibrated, mercury-displacement measurement arrangement together with a hinged, metal frame.

   Cantilever springs, instrumented with electric resistance strain gages have been used (personal communication). The springs are mounted on the cell and allowed to bear against the specimen. As the specimen deforms, the movement is sensed by the calibrated springs. (This method was adopted in this investigation and will be discussed in detail later.)

6. Circumferential belts of various types can be used as either a K^o (no lateral strain) sensor or as a lateral strain gage. In practice, the belt would be wrapped once around the specimen and secured. As the specimen deforms, the instrumented belt senses and indicates the movement. By monitoring the indications of deformation, the operator can, if desired, regulate the cell pressure to maintain K^o conditions. Generally, the belts have been employed primarily as K^o devices and instrumented with electric resistance strain gages. DiBiagio (6) used a calibrated metal band which was fastened by an elastic material. As the specimen diameter changed,

the indications were monitored visually. Whitmore (7) reported that the instrument was somewhat less than successful. Whitmore (7) experimented with a "belt" type of strain gage which consisted of a small-bore rubber tube filled with mercury. The mercury was used as the active gage in a Wheatstone Bridge circuit. Whitmore concluded that the instrument has potential value, but that additional development and testing were necessary.

Each of the above systems has certain advantages and disadvantages for low pressure triaxial work. In working with high confining pressures, most of the inherent disadvantages are much more prominent and may preclude the use of some systems.

In many of the systems, it is either necessary or highly desirable to see the interior of the triaxial cell. For this project such is not practicable and all techniques requiring interior visibility were not considered.

Manual, direct measurements of diameter changes were eliminated due to problems of sealing since the shafts of the micrometers would pass through the cell walls. In addition, making the measurements would be slow and would not be practical for dynamic work. Another difficulty is in the accurate determination of contact between the micrometer point and the specimen.

The capacitance systems appear promising. Mishu (4) reports on the use of such a gage and concludes that strain measurements on the order of 0.01 percent are possible for a 1.4-inch-diameter soil specimen. Mishu utilized the soil specimen itself as one part of the capacitor and a ring which surrounded the specimen as the other part. He states that the capacitance of the system depends on the soil type, the cell fluid medium, the ring surface area, the confining pressure and temperature. Of special note was the fact that his cell fluid (pure white glycerin) had to be changed after each two tests due to dielectric constant changes.

The capacitance measuring system was considered in this project as the second choice of systems and would have been explored for usage except that the first choice provided acceptable results. Investigation of the feasibility of a capacitance system for high pressure work would be worthwhile.

After considering the various techniques available, it was concluded that the most promising appeared to be one which employed cantilever springs instrumented with electric resistance strain gages. Development of this type of gage was begun and eventually a working system was devised. The development and usage of the instrument is described in the following text.

Use of Strain Gages Under Pressure

One of the problems involved in the use of a strain gage type instrument subjected to high pressures is the effect of pressure on the gages

themselves. This problem has been investigated by several persons, both theoretically and experimentally. Milligan (8) reports on the response of soil strain gages up to 140,000 psi and summarizes the results of recent investigations (up to 1965). Brace (9) discusses theoretical aspects of the effects and presents data regarding the effect for gages mounted on several different materials under pressures up to 10 kilobars.

Conclusions regarding the use of strain gages under high hydrostatic pressures are that the gages will perform satisfactorily provided suitable mounting techniques are utilized. Generally, mounting on a relatively smooth surface should be accomplished using a minimum thickness of cement and with a cement which will resist creep under the applied pressures. Cements utilized satisfactorily include epoxy cements and Eastman 910.

It has been shown (9) that the compressibility of the substrate will have an insignificant effect on the "pressure effect" of the gages. (The "pressure effect" is defined as being the algebraic difference between the indicated strain and the true strain occurring in a gaged material.) In addition, the pressure effect will be of a small value, i.e., approximately 1.1×10^{-4} strain units per 2 kilobar hydrostatic pressure and the effect will be linear.

Design of the Lateral Deformeter

The lateral deformeter design underwent several modifications on paper; however, the first working model has been used throughout the project without modification. Essentially, the instrument consists of a steel ring which attaches to the triaxial cell base. Attached to the ring are cantilevered metal strips which bear against the specimen. The strips are instrumented with electric resistant strain gages which sense the movement of the strips and therefore reflect the lateral deformation of the specimen. A photograph of the device is shown in Figure 5.

The ring (Figure 6) is made of structural grade steel at present. (Since the present instrument has been used almost daily in oil, corrosion has been insignificant; however, it is recommended that stainless steel be used.) The dimensions shown on the drawing are those necessary for the particular triaxial cell used in this investigation and will have to be adjusted to fit other test equipment.

The ring can accommodate twelve strips or springs. This will allow the instrument to measure at multiple points along the length of the specimen. At present, three springs are used. These are spaced at 120 degrees and bear against the specimen at midheight.

The taper of the upper part of the ring was selected to cause the springs to be initially preflexed when used with a 1.4-inch-diameter specimen. This allows measurement of both increases and decreases in the diameter.

The springs (Figure 6) are made of spring steel. The shape was selected in order to cause a greater amount of spring deformation to

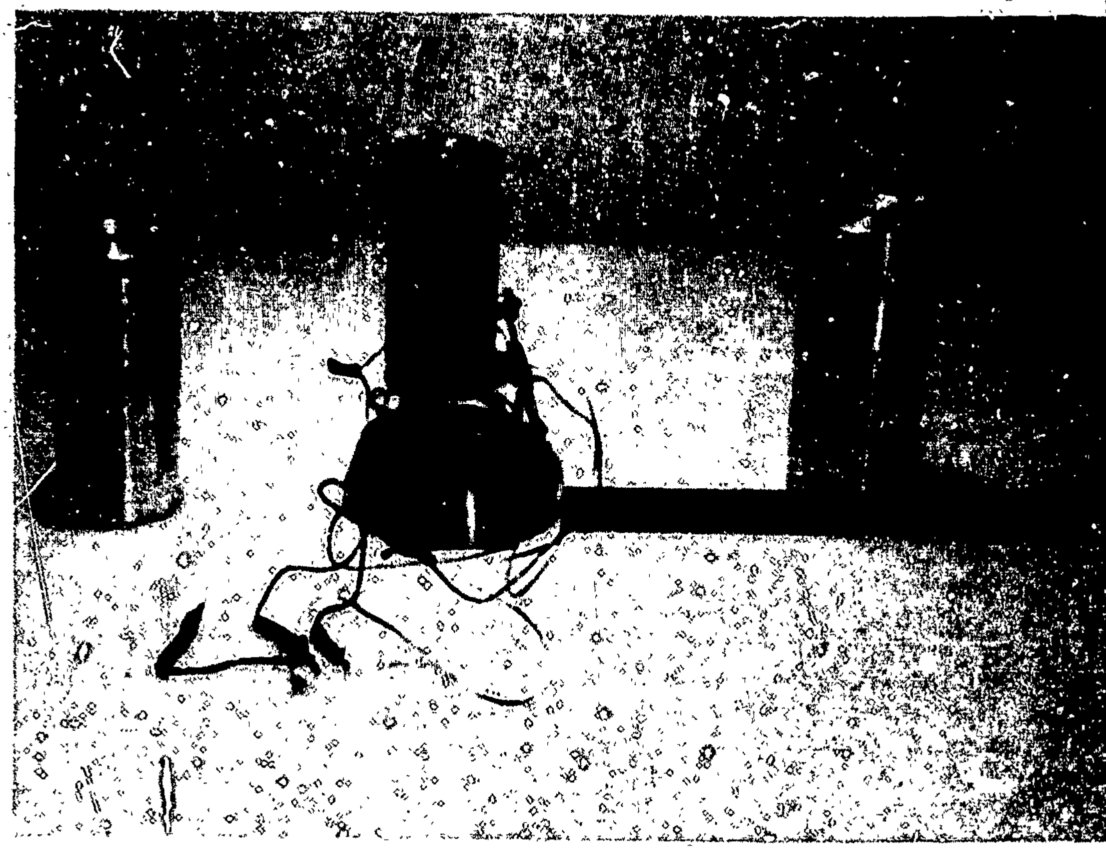


Figure 5. Lateral Deformeter and Calibration Blocks

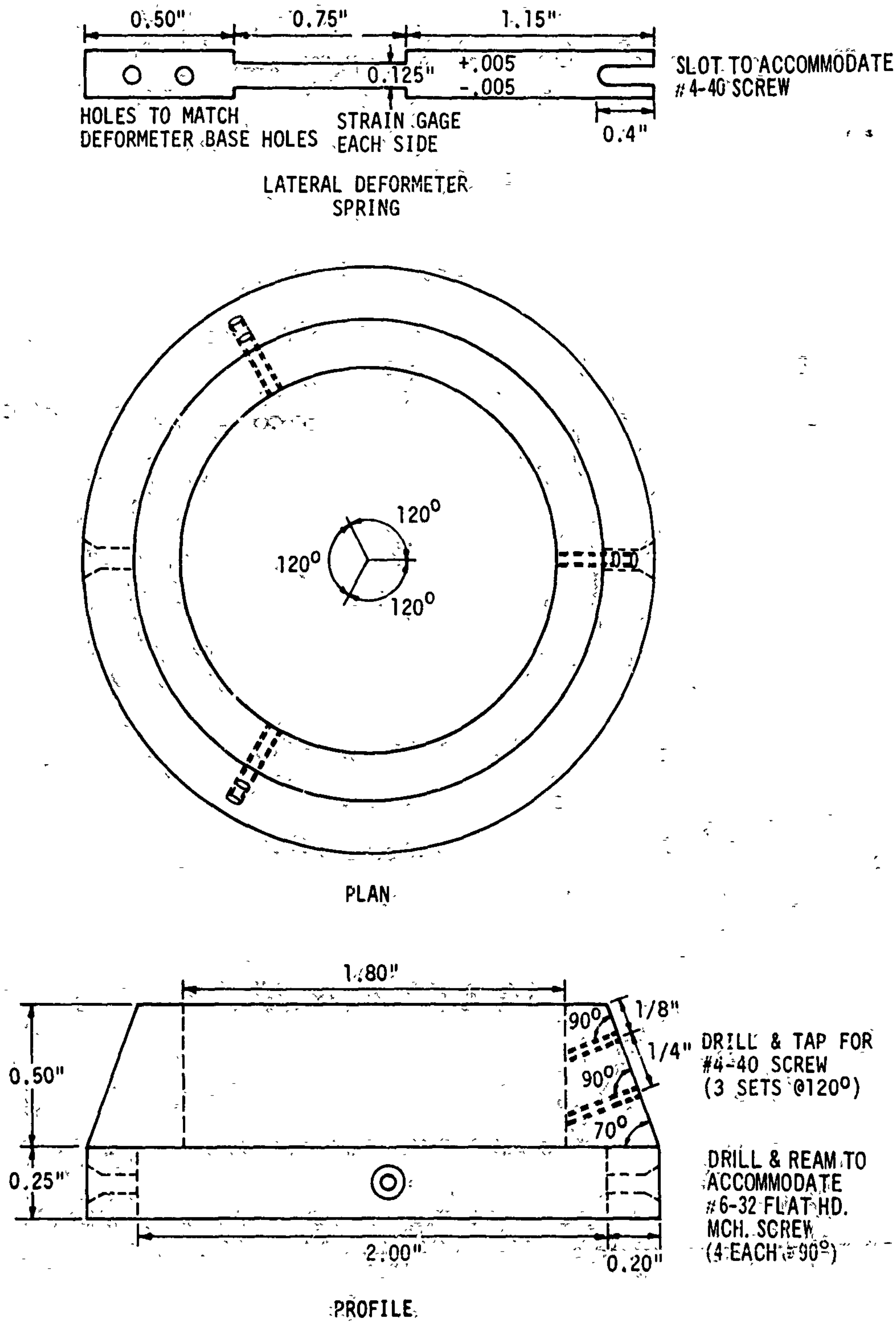


Figure 6. Lateral Deformeter

occur near the fixed end and, thereby, to increase the sensitivity of the instrument. The reduced section was dimensioned to accommodate a strain gage which is approximately 0.1 inch by 0.5 inch.

Strain Gages used on the deformeter are wire gages on a paper base. They are manufactured by University Precision Measurement Company of Ann Arbor, Michigan. Specifications are: Type 40, gage length 0.4 inch, 120 ohms resistance with gage factor of 2.06.

The gages were bonded to the springs with Eastman 910 cement using only the normal precautions for this cement. No problems have arisen with regard to gage application during the approximate 9-month use of the instrument.

Strain gage circuitry was in the form of a two-arm bridge. Gages were affixed to each side of all three springs and the three outer gages connected in series as were the three inner gages. The sensitivity of the instrument is indicated in the section under "Calibration."

Calibration

The calibration of the lateral deformeter was carried out under the following different conditions:

1. Machined calibration cylinders shown in Figure 5.
2. Mounted in the cell, using no specimen and under hydrostatic pressure.
3. Mounted in the cell, using a steel specimen, no membrane, and under hydrostatic pressure.
4. Mounted in the cell, using the steel specimen enclosed in a rubber membrane, and under hydrostatic pressure.

By means of the methods outlined, the effect of pressure on the deformeter was measured as was the indicated effect of a change in thickness of the membrane.

The basic calibration was carried out with the instrument mounted on the cell base under atmospheric pressure only. The calibration blocks (Figure 5) were machined to produce successively larger diameters in steps upon which the deformeter springs could bear. The blocks were positioned so that the deformeter was calibrated over a range of diameters from 1.20 inches to 1.70 inches. The resulting correlation was found to be 13.27 microinches per inch per 0.001 inch of diameter change.

The effect of pressure on the deformeter itself was determined with the instrument mounted on the cell base, using no specimen, and subjecting it to pressures up to 10,000 psi. Figure 7 presents the results of this determination. The effect is to indicate an apparent diameter decrease.

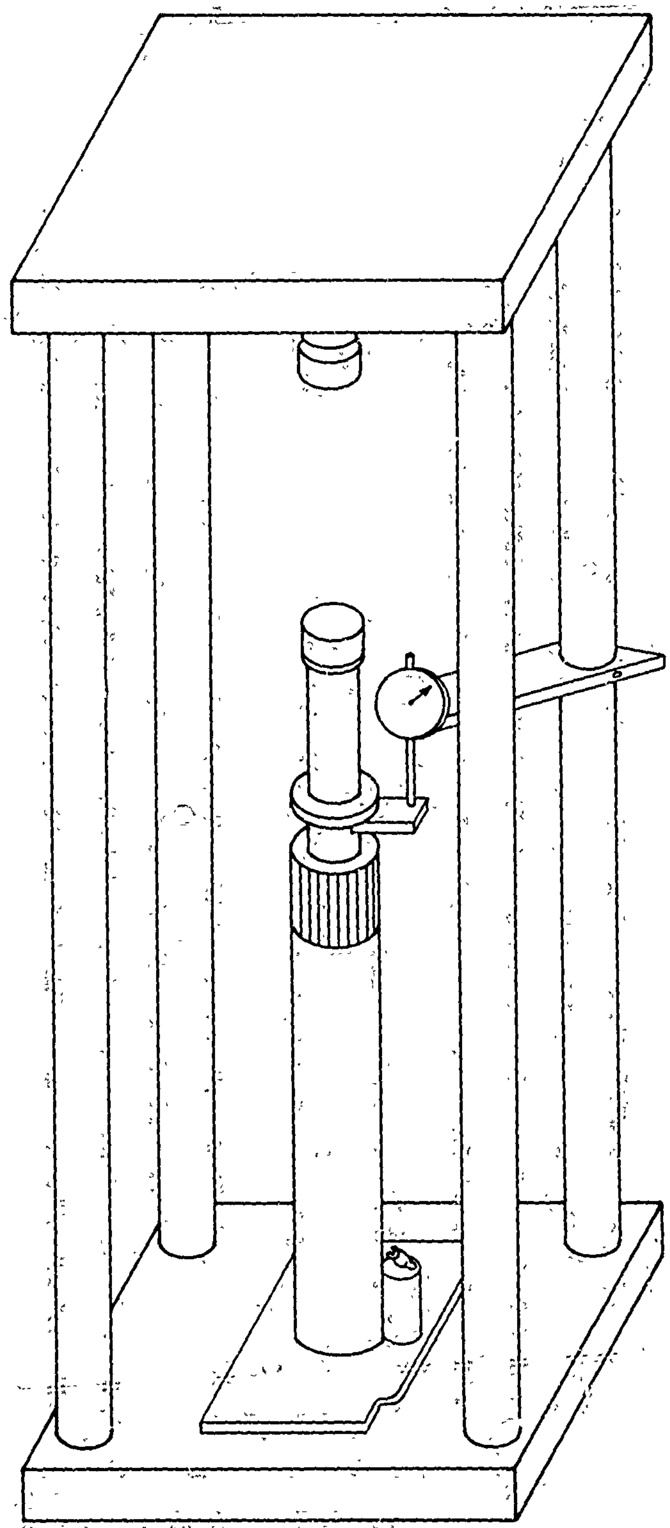


Figure 15. Specimen Forming Frame

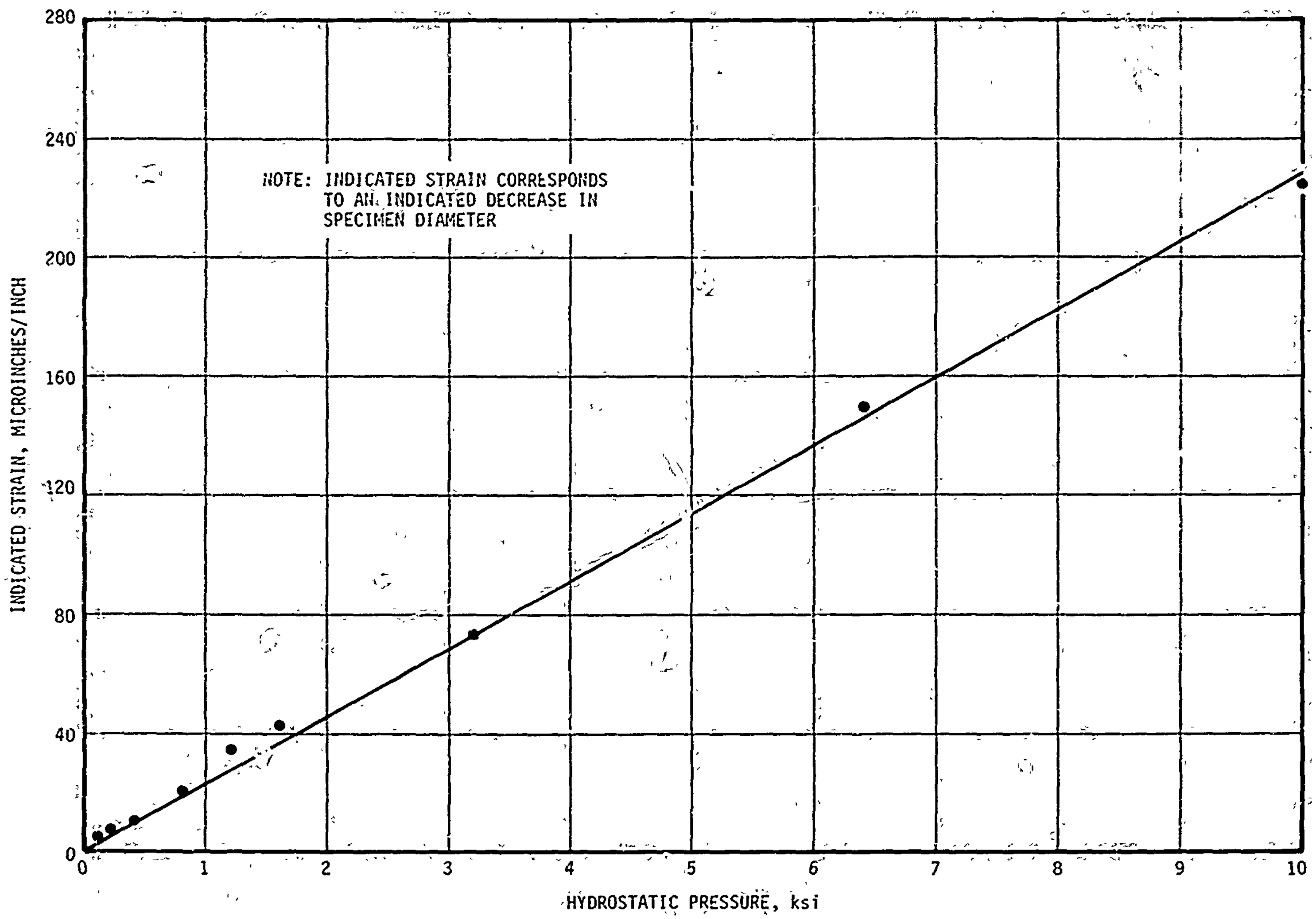


Figure 7. Calibration of Lateral Deformeter Under Hydrostatic Pressure

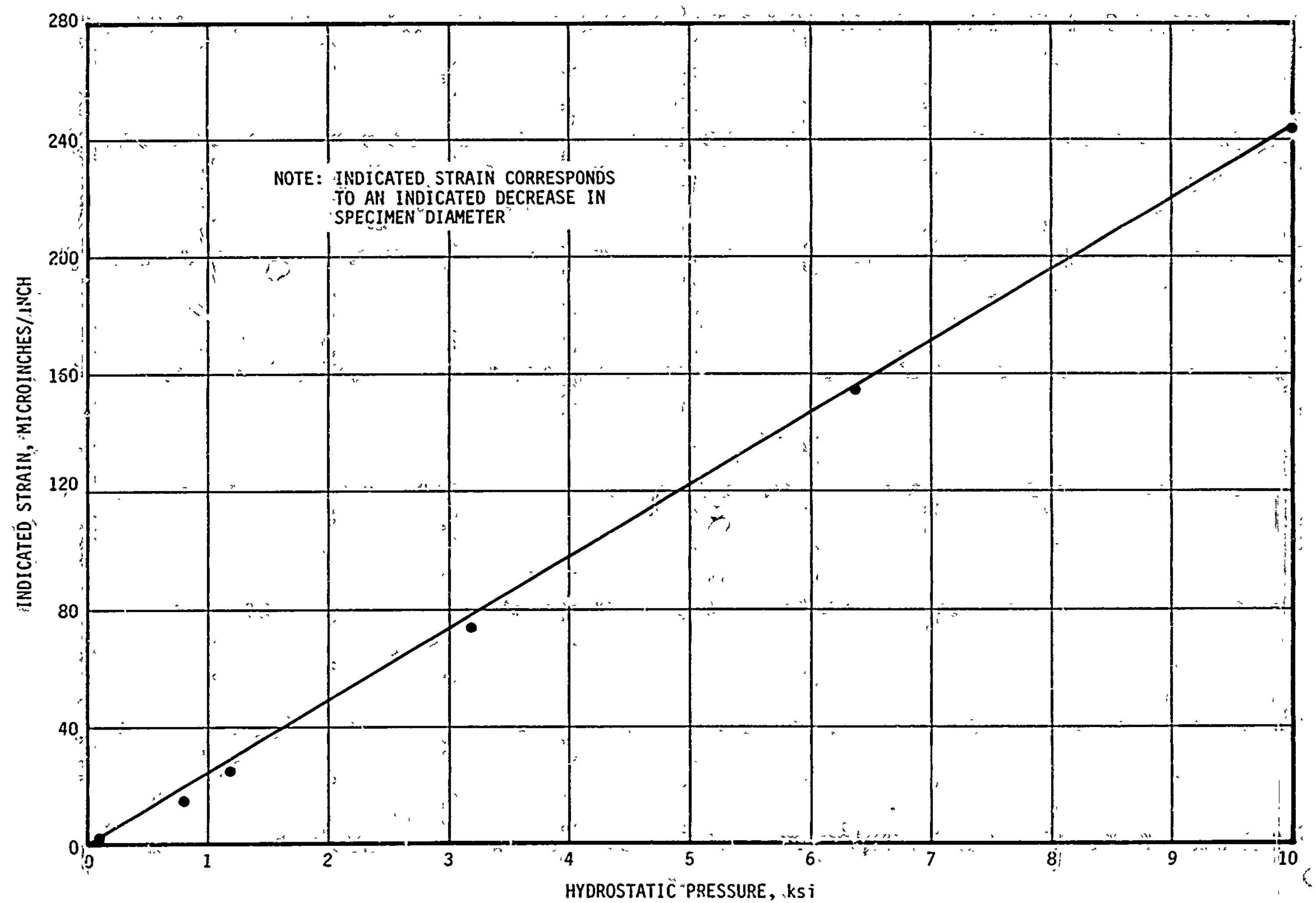


Figure 8. Calibration of Lateral Deformeter With Metal Specimen

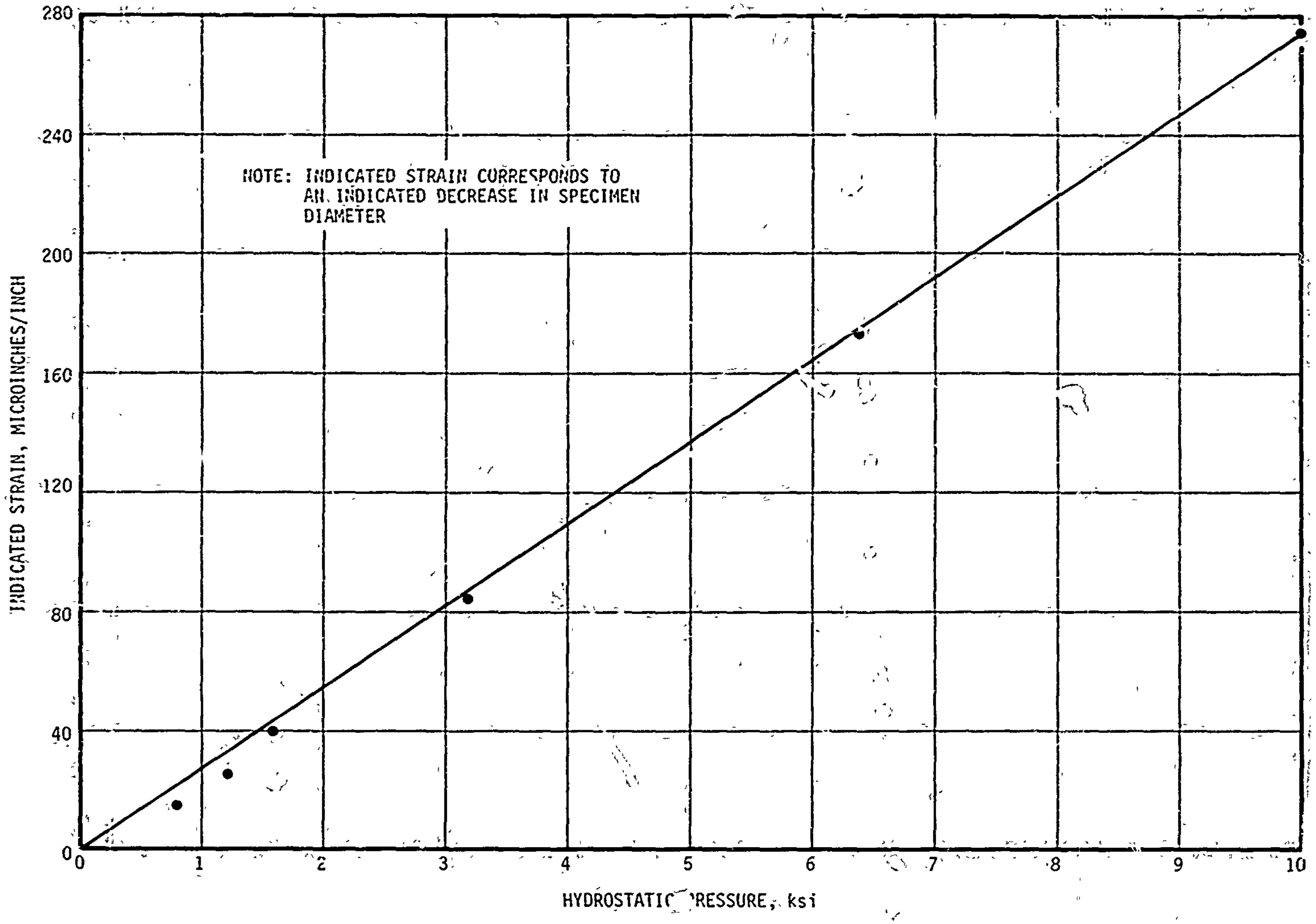


Figure 9. Calibration of Lateral Deformeter With Metal Specimen and Membrane

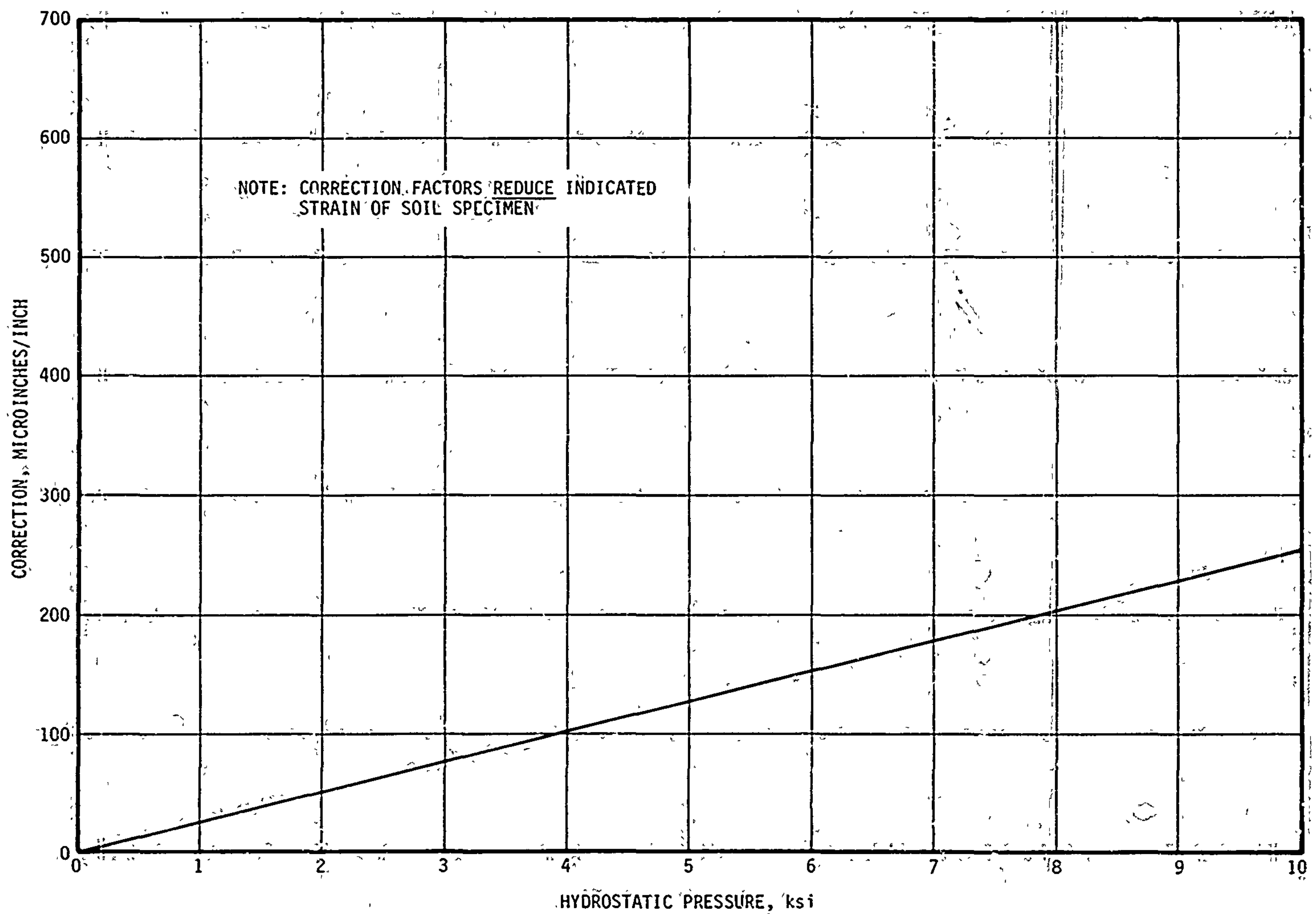


Figure 10. Lateral Deformeter Correction Factor vs Pressure

CHAPTER IV

SOILS AND SPECIMEN FORMING

Soils

Two soils were tested. Bot soils were furnished by WES in an air-dried state. The soils had been sieved through a No. 4 sieve to remove large particles, organic and other foreign matter.

One soil was a clayey sand obtained from the McCormick Ranch test site near Albuquerque, New Mexico. This soil will be referred to as the McCormick Ranch Sand. It is classified as SC according to the Unified Soil Classification System. The gradation curve and the Atterberg limits are shown in Figure 11. The desired dry unit of this soil was 117 pcf at a moisture content of 11.4%.

The second soil was a silty clay obtained from the Watching Hill test site at the Defence Research Establishment, Suffield, Canada. This soil will be referred to as the Watching Hill Clay. It is classified as CL. Gradation and Atterberg limits are shown in Figure 12. The desired dry unit weight of this soil was 93 pcf at a moisture content of 12.5%.

Speciren Forming

The soil was received in metal containers, each holding approximately 70 pounds. The soil in each can was thoroughly mixed in a dry state, after which, water was added to produce the desired water content. The water and soil were first mixed manually, then with a mechanical mixer and, finally, manually. The moist soil was placed in plastic bags and stored in a humid room for a minimum of seven days prior to forming. The moisture content was checked immediately prior to forming.

The forming mold (Figure 13) is a stainless steel tube, 1.385-inch I.D. witl a wall thickness of 1/8 inch. The compacting pistons are of aluminum and were machined to produce a close fit inside the tube. The technique used during molding allowed the tube to float freely and the soil to compact from both ends toward the middle.

The specimens were nominally 1.4 inches in diameter by 3 inches in length. The amount of moist soil sufficient to produce the desired density was weighed and placed in the mold. During the charging of the mold, the bottom piston was held in position to extend approximately $\frac{1}{2}$ inch into the mold. A funnel was used to prevent loss of soil and the soil was lightly rodded until the soil surface was just below the mold top. The top piston was put in position and the entire assembly placed in a loading frame (Figure 14 and Figure 15). A hydraulic jack forced the pistons into the mold, thereby compacting the soil. The length of compacted specimen was determined by gaging with a dial indicator to within 0.001 inch. During the molding, both the top and bottom piston moved into the mold while the mold was rotated to minimize friction. When the proper length was reached, the load was held to maintain such length for a period of

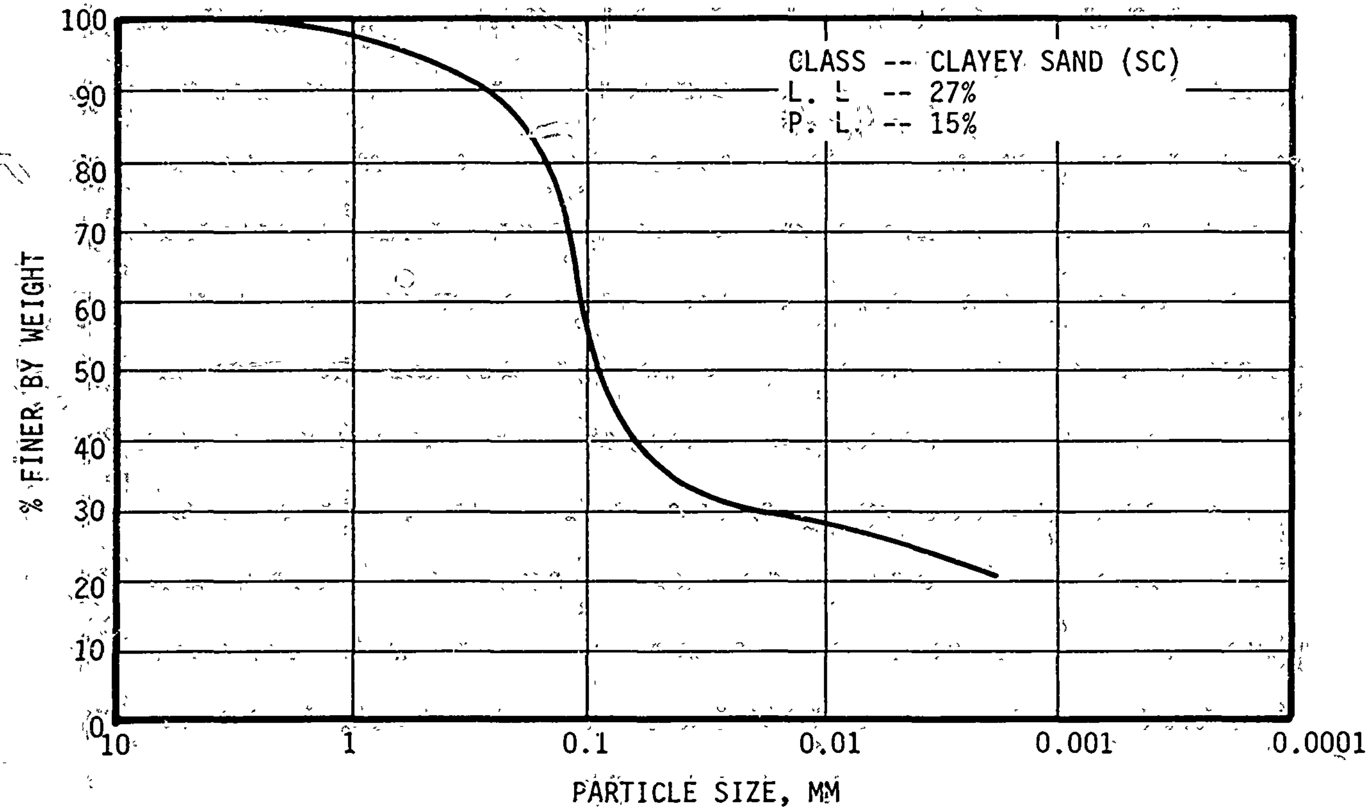


Figure 11. McCormick Ranch Sand Gradation

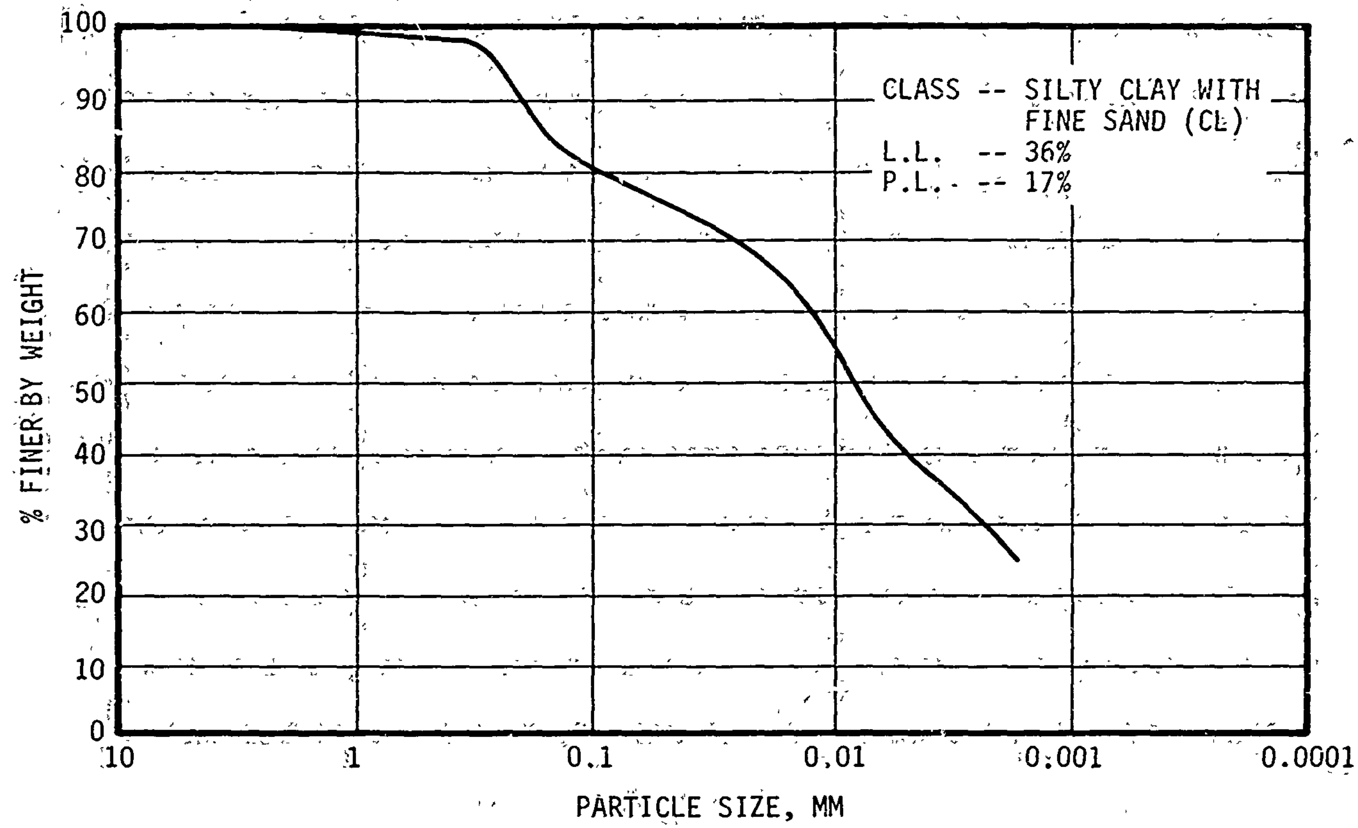


Figure 12. Watching Hill Clay Gradation

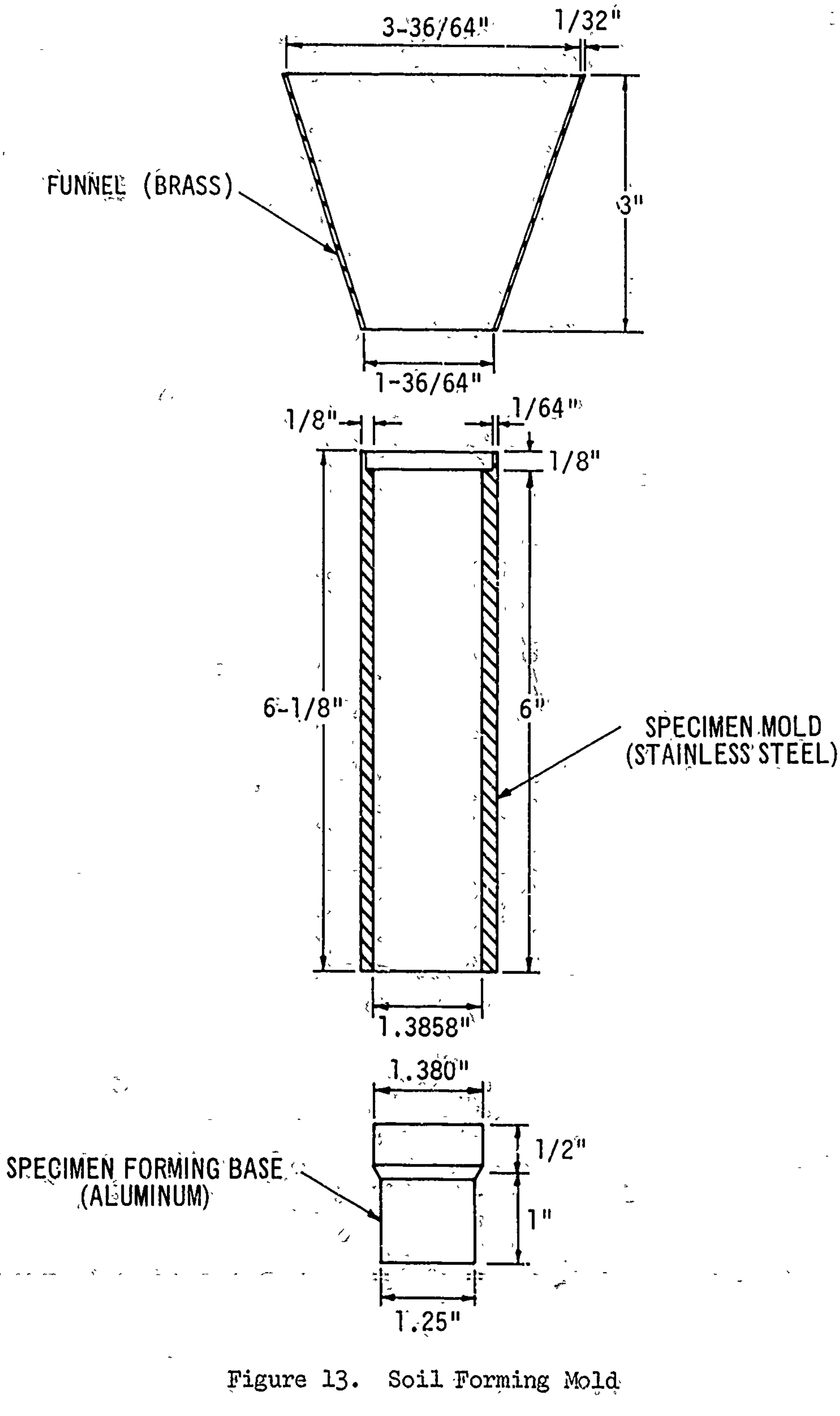


Figure 13. Soil Forming Mold

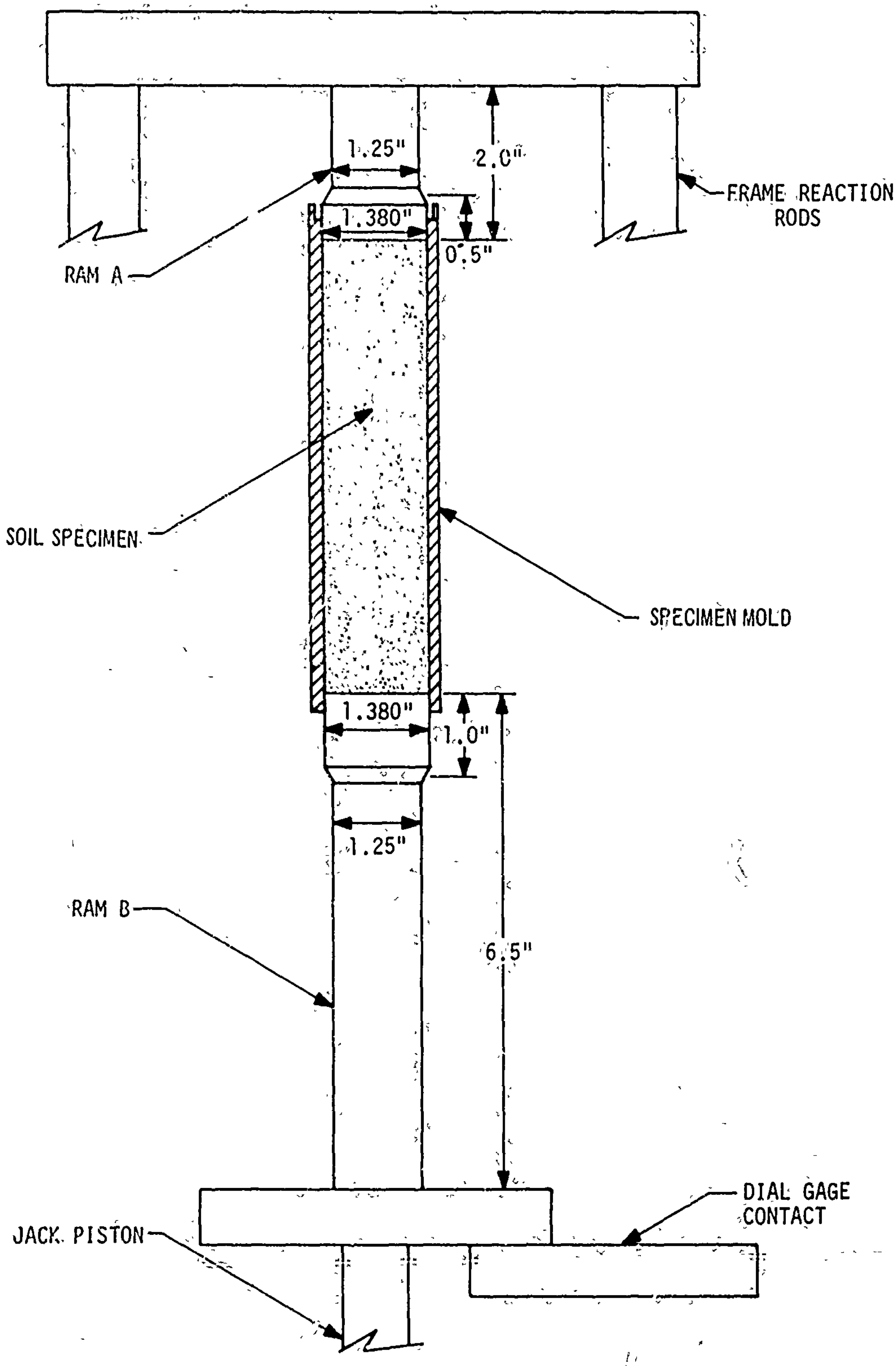


Figure 14. Specimen Formation

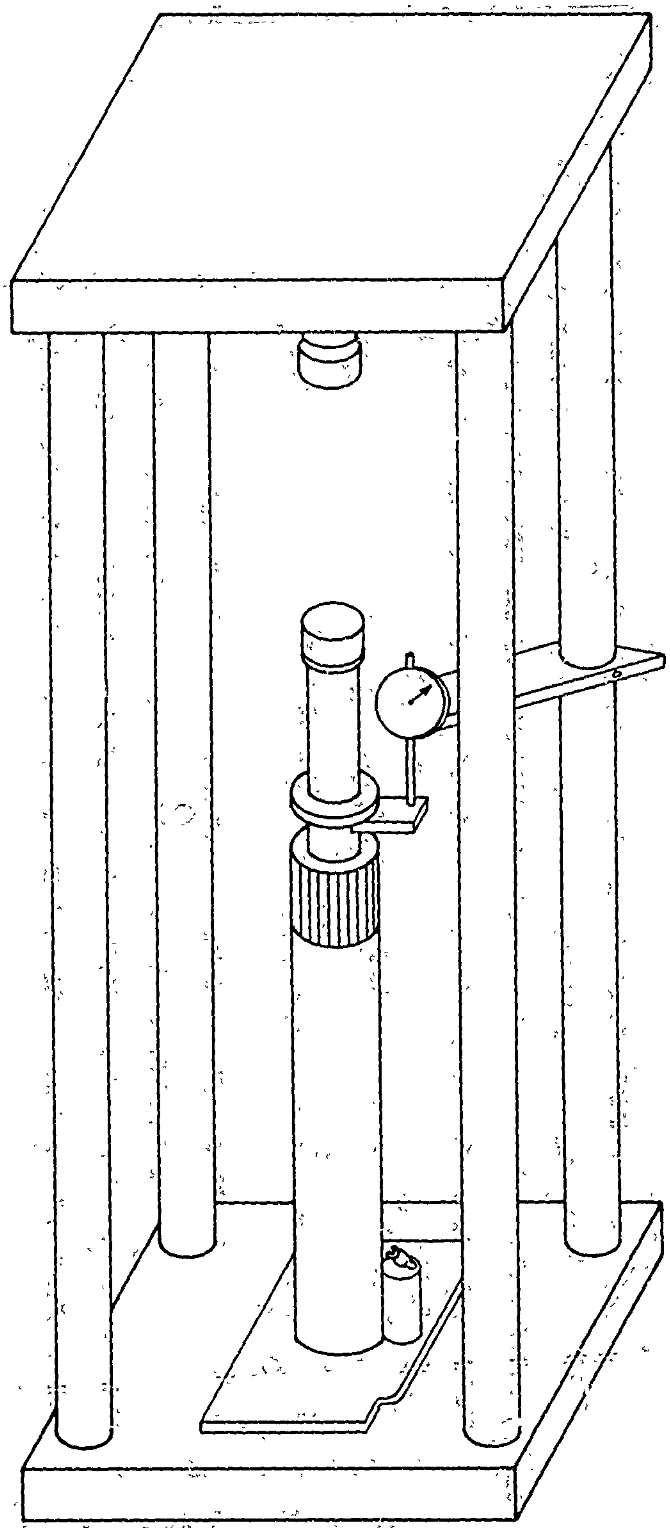


Figure 15. Specimen Forming Frame

30 seconds. After this, the load was released and the forming pistons removed. Extrusion of the specimens was accomplished by hydraulic power. A photograph of the equipment is shown in Figure 16.

The extruded specimens were each weighed and checked for parallel ends. The height was measured and the diameter determined at the top, middle, and bottom. The density was calculated and only those specimens that were within ± 0.2 pound per cubic foot of the desired density were accepted. Each specimen was wrapped in six layers of Saran Wrap, placed in three plastic bags (each bag individually sealed) and stored in a humid room until tested.

The McCormick Ranch Sand specimens were formed in batches of 25 as needed for testing and stored for a minimum of 7 days prior to testing.

The Watching Hill Clay specimens were all formed prior to the beginning of testing operations.

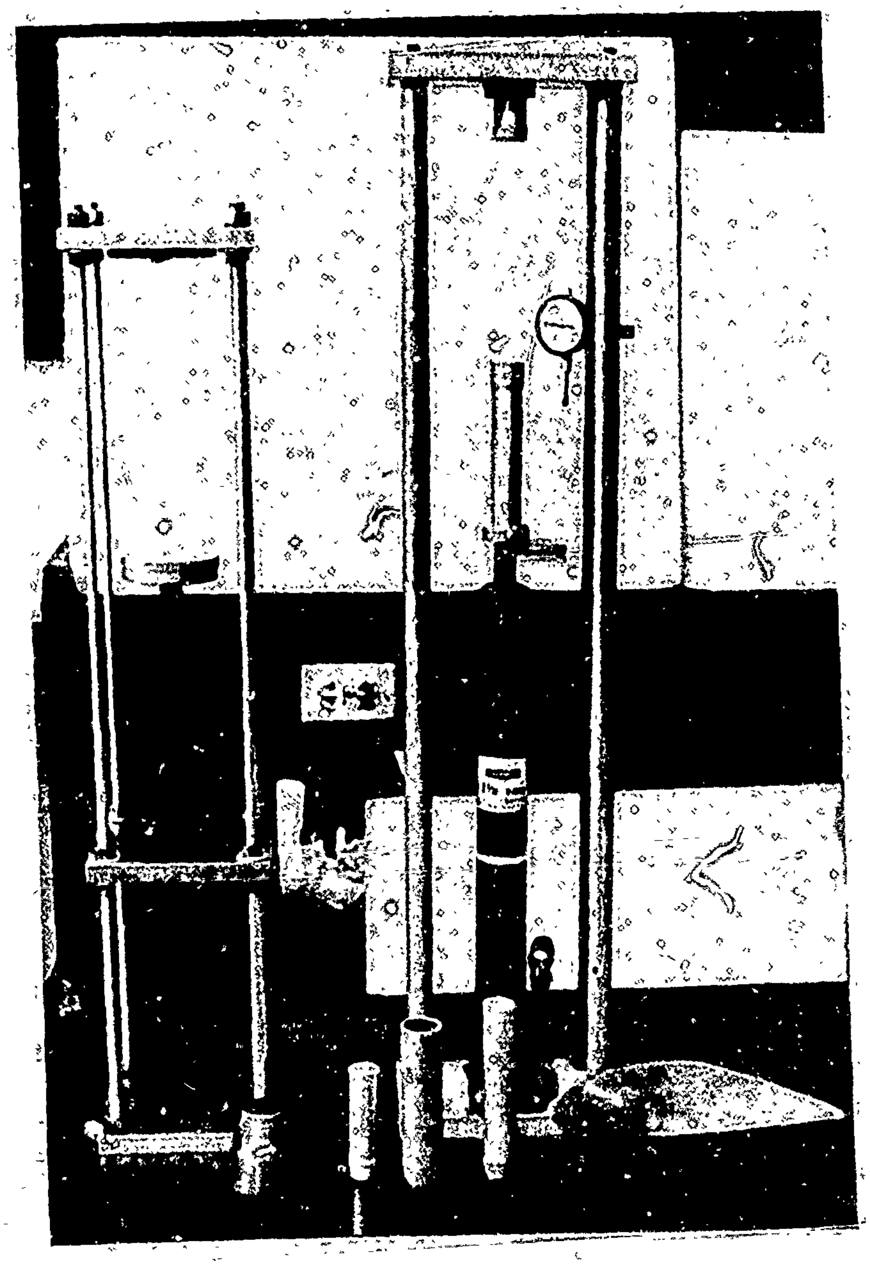


Figure 16. Specimen Forming Equipment

CHAPTER V

TRIAXIAL TESTS: TYPES AND PROCEDURES

Types of Tests

The test program included the following basic types of tests:

1. Hydrostatic Compression tests were performed on all specimens which were to be tested in shear under confining pressures greater than atmospheric.

2. Triaxial Shear tests were conducted where the shear loads were applied (after the desired confining pressure had been effected) at constant rates of strain. Loading was continued to failure or to a desired strain value.

3. Cyclic loading tests were accomplished for both Hydrostatic Compression and Triaxial Shear. In Hydrostatic Compression, the pressure was raised in regular increments up to the desired pressure level. Unloading was conducted using the same pressure increments and reloading followed. In Triaxial Shear, the loads were applied at a constant strain rate up to a desired stress level and then the specimen was unloaded at the same strain rate. Reloading followed. The number of load-unload cycles varied from one to four.

4. "Constant Stress Ratio" tests were performed. After the application of the hydrostatic compression phase, the shear stage was accomplished by increasing the confining pressure together with the axial load so that a constant ratio existed between σ_r and σ_a. Axial loading was at a constant strain rate. The lateral pressure was manually controlled and loading was continued either to failure or to maximum available confining pressure (10,000 psi). Cyclic loading was accomplished in some tests.

5. K^o, or "No-Lateral-Strain," tests were accomplished by maintaining a constant specimen diameter by adjusting the confining pressure while increasing the axial load at a constant rate of strain. Cycle loading (one cycle only) was accomplished in some tests.

Test Procedures

Test Preliminaries

Specimens were selected at random from those previously formed. The

one to be tested was removed from its wrappings, measured for length and diameter, and weighed. The volume was determined by mercury-displacement techniques.

The specimen was placed on the base cap and enclosed in a single rubber membrane (0.025 inch thick). A rubber band was used to seal the membrane to the cap.

Next, the lateral deformeter was carefully lowered over the specimen and secured to the base by the screws. The assembly was checked to assure that the specimen was firmly seated, then the top cap was placed in position. The membrane was pulled wrinkle-free over the top cap and secured by a rubber band.

The cell cylinder was attached to the cell base and the internal electrical connections were made.

Oil (SAE No. 20) was poured in the cylinder and the cell gland was screwed into position. Care was used to ensure that no air was entrapped. The cell was filled to a level such that oil would be displaced and forced out as the gland was screwed down.

The load piston was inserted into the cell through the gland and into position in the piston guide portion of the specimen top cap. Contact of the piston with the cap was detected by the completion of the electrical circuit and the lighting of the lamp. As the piston moved into the cell, drainage of the fluid displaced by the piston was accomplished through a valve near the top of the cylinder.

That completed the cell assembly. The unit was then moved to the testing machine and all measuring components connected and checked. Photographs of the cell and other apparatus are shown in Figures 17, 18, and 19.

The specimen was subjected to hydrostatic pressure of 5 psi and zero readings of height and diameter were recorded.

Application of Hydrostatic Stress

The shear stage of the tests began from an initial hydrostatic pressure which was some value between zero (atmospheric) and 10,000 psi. The hydrostatic pressures used were 0, 100, 200, 400, 800, 1200, 1600, 3200, 6400, and 10,000 psi.

For a given test, the pressure was increased in increments corresponding to those shown above up to the desired value. Under each pressure increment, the changes in height and diameter were determined immediately upon application of the stress. The air-hydraulic pump was used to apply a pressure to within approximately 200 psi less than that desired and the final adjustment made with the manual pressure control system.

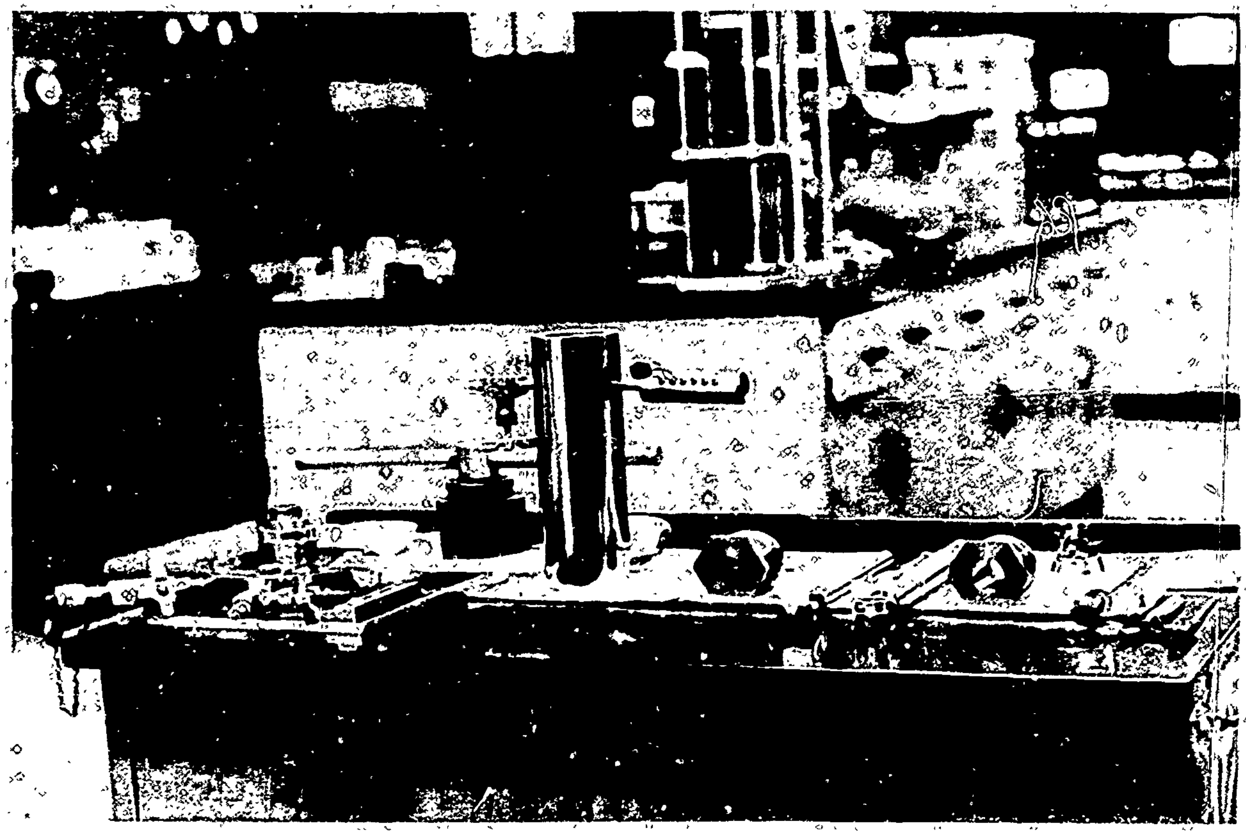


Figure 17. Triaxial Cell and Associated Equipment

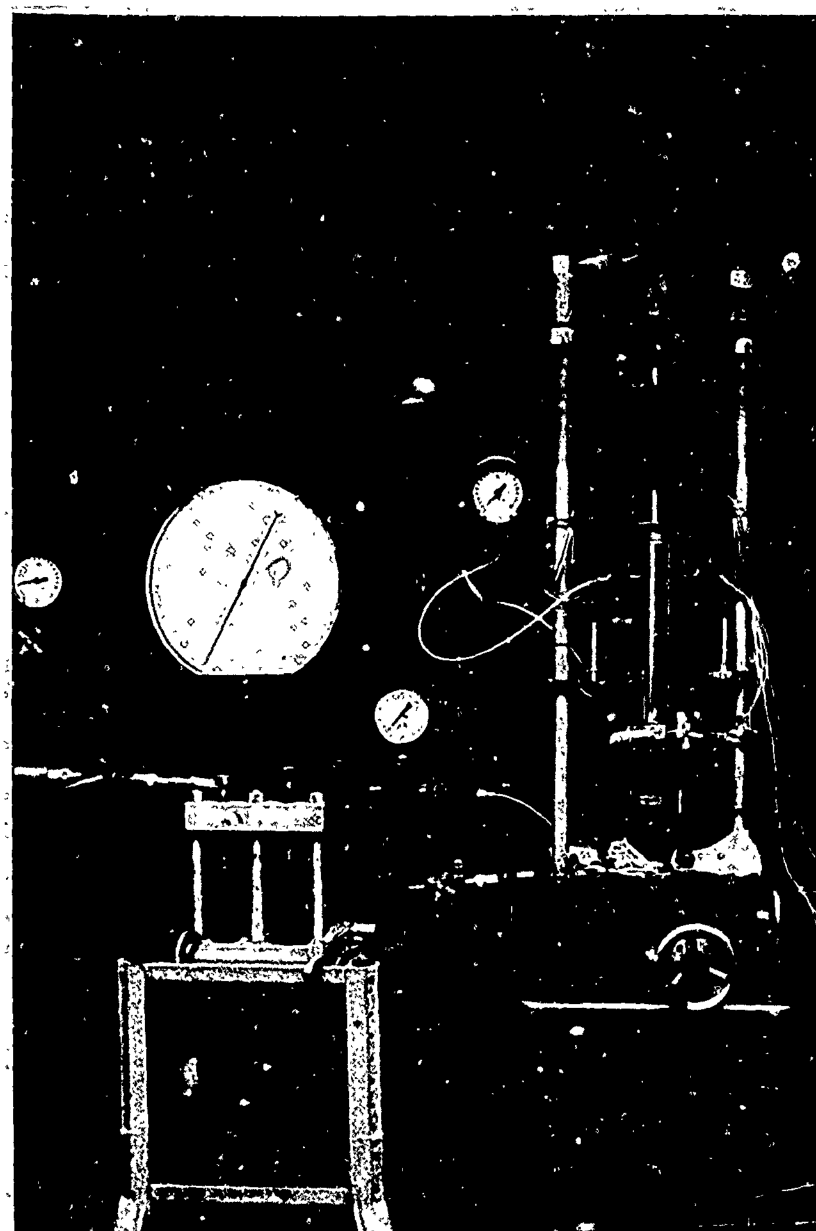


Figure 18. General View of Test Setup

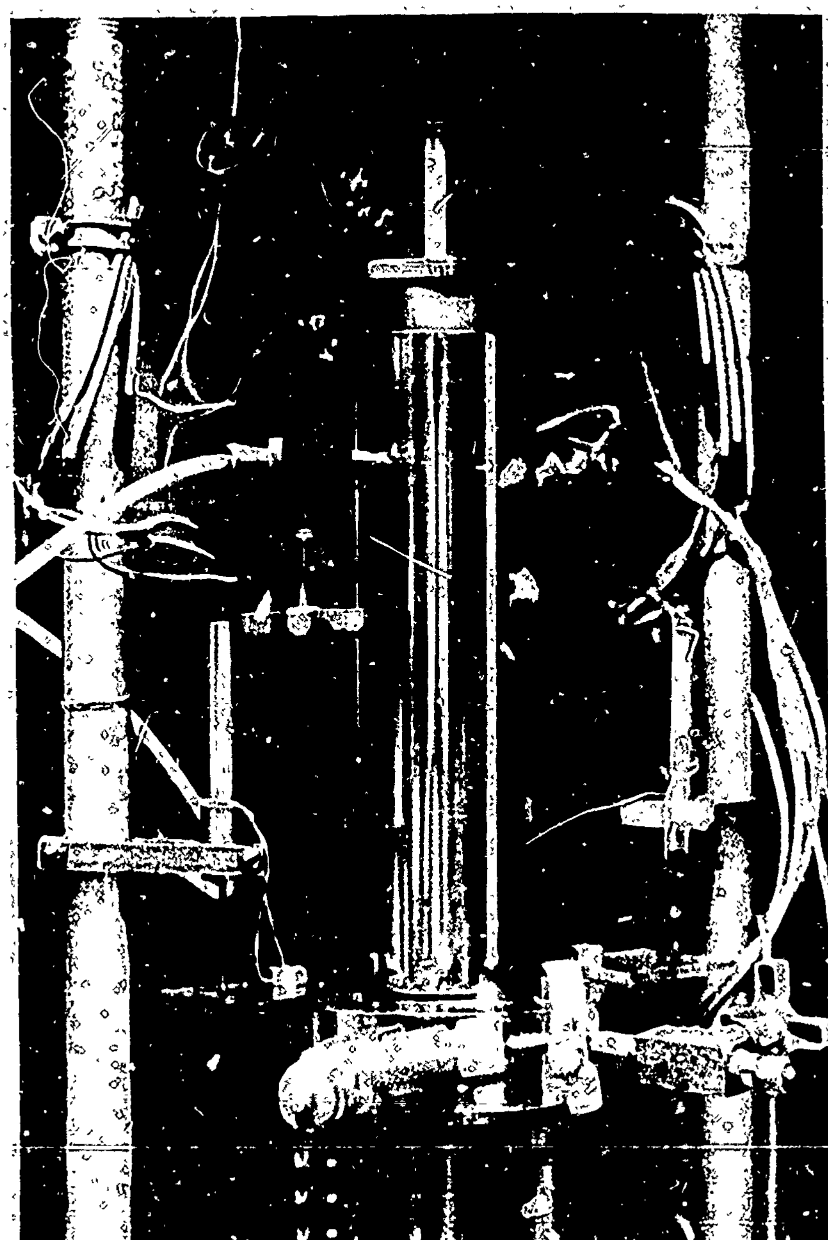


Figure 19. Closeup View of Test Setup

For the cyclic hydrostatic tests, the specimens were loaded incrementally to the desired stress level, unloaded, and reloaded incrementally with height and diameter changes recorded after the application or removal of each pressure increment.

Some tests, particularly the K^o and certain of the constant stress ratio, required rapid increases in confining pressure. For these tests it was necessary to resort to a manually operated hydraulic pump to apply the approximate pressure and to effect precise control by means of the piston-cylinder arrangement.

Application of Axial Load

The axial load applied to the specimens was effected by a Wykeham-Farrance constant strain loading machine. The rate of load application for all tests was 0.015 inch per minute.

The load was transmitted to the specimen by one of the two following sized pistons:

Piston Diameter	Test in Which Used
7/8 inch	Triaxial with constant lateral pressure
1.4 inches	K^o; Constant Ratio σ_r/σ_a

For the hydrostatic pressure application the piston was not in contact with the specimen top cap except when desired to determine length changes. To add axial loads, the piston was brought into contact with the top cap by manually adjusting the testing machine and the load then applied mechanically. To unload axial load, the machine was stopped at the predetermined stress level and then the direction of travel was reversed. The load was removed at the same rate at which it was applied.

For the K^o and the constant stress ratio tests, the piston (1.4-inch diameter) was brought into contact with the specimen after the application of the 5-psi seating pressure. Axial loads were then applied mechanically.

Measurements of Specimen After Testing

Upon completion of the loading phase (whether hydrostatic and/or shear), final readings of height and diameter changes were taken immediately after the load removal, but with the 5-psi seating load remaining. After removal from the cell, the specimen was measured for length and diameter, the shape was noted and the volume was measured by mercury displacement. The water content was determined by drying the entire specimen.

CHAPTER VI

RESULTS AND DISCUSSION

Test Program

The program included the testing of the two soils under a wide variety of test conditions. An initial test program was set up and followed for the McCormick Ranch Sand, the first soil tested. The lateral deformeter was developed prior to the beginning of testing and was used for all tests. After completion of the test program for the sand, a review of the test capabilities indicated the desirability of a modification in the test program for the Watching Hill Clay. The test program for the two soils follows. All tests were of the unconsolidated-undrained (U-U) type.

McCormick Ranch Sand

Two basic tests were made on the sand. These were the "normal" triaxial and the "constant stress ratio" triaxial. In the "normal" triaxial tests, cyclic loading was accomplished at approximately 35% and 75% of the maximum strength. Four confining pressures, representative of the entire confining pressure range, were to have been utilized. Additional confining pressures were added during the test program in order to better define the soil properties and behavior. The following "normal" triaxial tests were accomplished:

Confining Pressure, psi	Type Test
100	Triax., Cyclic @ 35% and 75%
200	" " " " " "
400	" " " " " "
800	" " " " " "
1,200	" " " " " "
1,600	" " " " " "
3,200	" " " " " "
6,400	" " " " " "
10,000	" " " " " "

Constant stress ratio tests were made at the following ratios of confining pressure to axial pressure:

(1) 0.4
(2) 0.6
(3) 0.8
(4) 1.0 (Hydrostatic Compression Test)

Cyclic loading was accomplished at approximately 75% of the noncycled "failure" load.

A minimum of 3 specimens was tested for each condition.

Watching Hill Clay

Prior to the initiation of testing of the clay, a conference was held with representatives of Georgia Tech and WES in attendance. A testing program was set up for the Watching Hill Clay which reflected the increased capabilities for radial deflection measurement. The following program was adopted:

1. Normal triaxial tests at confining pressures of 0, 100, 200, 400, 800, 1200, 1600, 3200, 6400, and 10,000 psi.

2. Cyclic triaxial tests wherein both the hydrostatic pressure was cycled once and the shear load was cycled at approximately 35% and at 75% of the failure load.

3. Constant stress ratio tests wherein an initial hydrostatic pressure was applied and, thereafter, the lateral and the axial stresses were increased at a constant ratio.

   The following program was accomplished:

σ_r/σ_a	Initial Hydrostatic Pressure, psi
0.4	0, 100, 200, 800, 1600, 3200
0.6	0, 100, 200, 400, 800, 1600, 3200
0.8	0, 100, 200, 800, 1600, 3200
0.9	0

4. "No-Lateral-Strain" (K^o) tests were performed by applying an initial hydrostatic pressure and, thereafter, loading axially at 0.015 in. per min. The lateral pressure was adjusted as necessary to maintain a "no-lateral-strain" condition. After saturation was reached, the specimen was unloaded. Only one specimen per test condition was utilized. The following hydrostatic pressures were used: 0, 100, 200, 400, 800, and 1600 psi.

5. Cyclic "No-Lateral-Strain" tests were made in a manner similar to those in Item 4, above, except that the loads were cycled at an axial load of approximately 50% of the saturation load. Two specimens were used for each of initial hydrostatic pressures indicated above.

Volume-Change Calculations

Volume changes of the soils were based upon deformed shapes as determined by measurements made on tested specimens.

The deformed shapes of many different tests specimens were measured by means of dial indicators. The results of these measurements were studied and a generalized, characteristic deformed shape was assigned to each soil.

The McCormick Ranch Sand was found to conform closely to the shape shown in Figure 20b. The specimen ends were therefore assumed to undergo no deformation and the deformation was assumed to be linear from both ends toward the center.

The clay, which was relatively more compressible than the sand, was found to have a shape like that shown in Figure 20a. The curved portions of the shape were approximated by straight lines as indicated by the dashed lines. The positions of the straight line segments were correlated with confining pressure and the volume calculations were based on the correlated positions.

The accuracy of the recorded measurements of both axial and lateral deformation of the soil specimens are considered to be within $\pm$ 0.0005 inch.

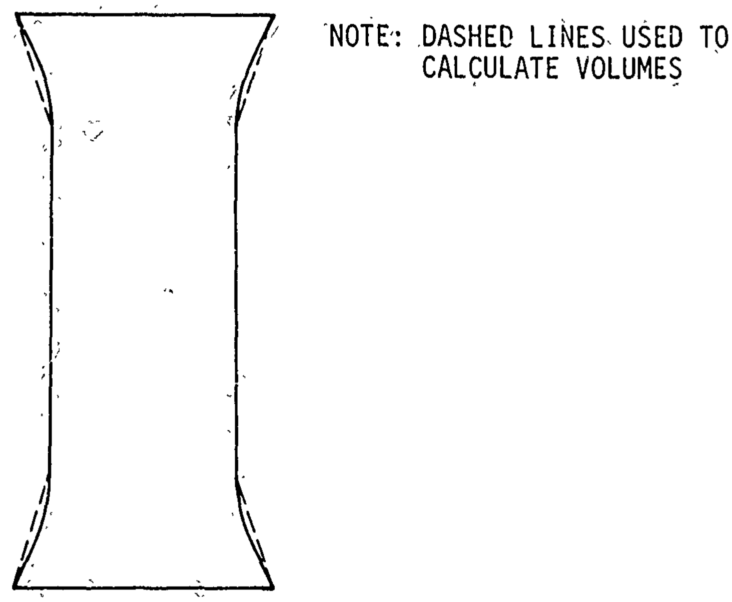
An error of 0.0005 inch in both radial and axial measurements of a cylinder 1.4" x 3" would cause an error of approximately 0.1% in the calculated volumetric strain, $\Delta V/V_o$. The effect of a 0.1% error in volumetric strain on the determination of bulk modulus will depend upon the rigidity of the material itself and upon the stress increment over which the strain is measured. Under the test conditions used in this project, the bulk modulus of tested materials should be within the following limits:

True Bulk Modulus	Probable Error
10,000 psi	$\pm$ 3%
50,000	$\pm$ 7%
100,000	$\pm$ 10%
300,000	$\pm$ 15%
600,000	$\pm$ 25%

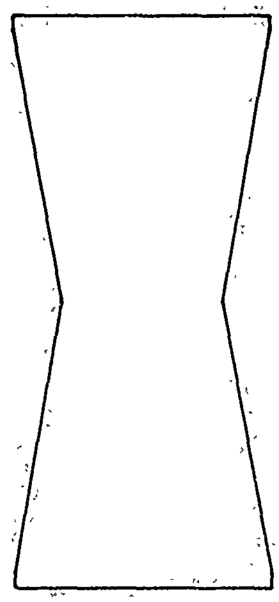
Presentation of Data and Results

The results of the test programs consist of the computer calculation printout of the data reduction for each test and of comparative displays of the stress-strain behavior of the soils. For the McCormick Ranch Sand, the individual stress-strain curves are presented in Volume II, Section I, and the computer printout sheets are in Volume III, Section I. Corresponding curves and sheets for the Watching Hill Clay are contained in Volume II, Section II, and Volume III, Section II, respectively.

The various types of curves developed from the data are shown in Figure 21. A list of all curves presented is shown in Tables 1 and 2. From this list, a variety of curves, representative of the entire range, have been grouped to illustrate the effects of pressure and state of stress. These "average" curves are included at the end of this chapter and are discussed individually in the following section.



20a. WATCHING HILL CLAY TYPICAL
DEFORMED SPECIMEN



20b. McCORMICK RANCH SAND TYPICAL
DEFORMED SPECIMEN

Figure 20. Deformed Shapes of Tested Specimen

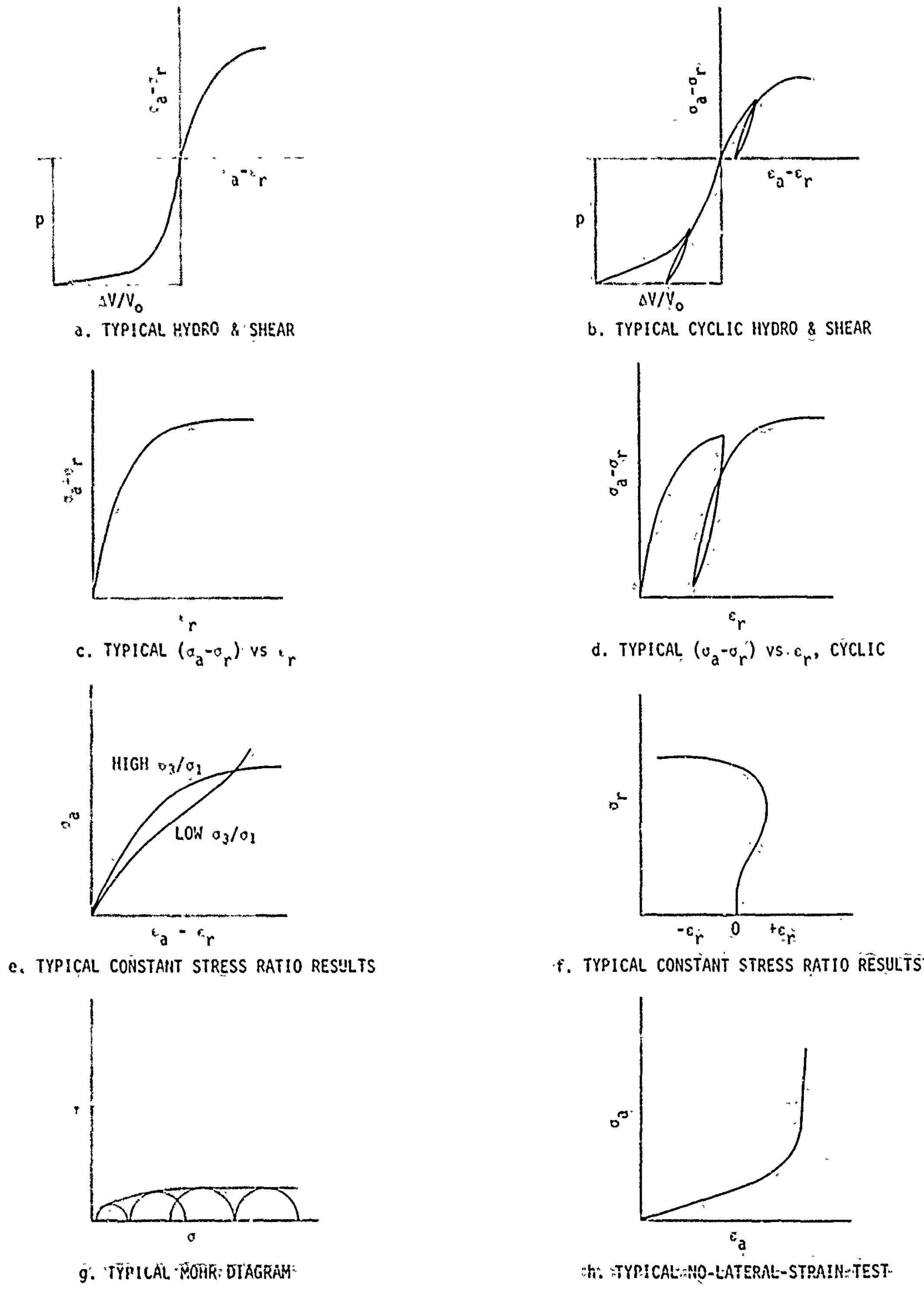


Figure 21. Typical Data Plots

Table 1. Graphical Results of McCormick Ranch Sand Tests

Type Test	Hydrostatic Compression Stage	Shear Stage
Triaxial (Incl. cyclic)	p vs $\Delta V/V_o$	$(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$, for all specimens
		$(\sigma_a-\sigma_r)$ vs ϵ_r, for typical specimens only
Constant Stress Ratio	p vs $\Delta V/V_o$	$(\sigma_a \quad)$ vs $(\epsilon_a-\epsilon_r)$, for all specimens
		σ_a vs ϵ_r, for typical specimens only

Table 2. Graphical Results of Watching Hill Clay Tests

Type Test	Hydrostatic Compression Stage	Shear Stage
Triaxial	p vs $\Delta V/V_o$	$(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$, for all specimens
		$(\sigma_a-\sigma_r)$ vs ϵ_r, for typical specimens only
Constant Stress Ratio	p vs $\Delta V/V_o$	$(\sigma_a \quad)$ vs $(\epsilon_a-\epsilon_r)$, for all specimens
		σ_r vs ϵ_r, for typical specimens only
No Lateral Strain	p vs $\Delta V/V_o$	σ_a vs ϵ_a

Discussion

General

When a soil specimen is subjected to undrained hydrostatic compression, there is a volume reduction. The amount of volume reduction will depend upon many factors, and for a given soil, these include initial void ratio and water content. Upon application of the hydrostatic pressure the soil skeleton compresses, and as a consequence, the gas in the pores must compress or go into (or partially into) solution in the pore fluid. There is undoubtedly some volume change of the fluid also; however, it is probably small under normal circumstances until the gas is almost completely driven into solution and the soil becomes saturated.

If one assumes that the compressibility of the soil skeleton itself

is constant and that the change in volume of air (whether compressing or going into solution) is directly proportional to changes in pressure, then the compressibility of the soil mass should be a constant. This should hold true until saturation is complete and then a new compressibility will occur which would have a greater value than that of the initial compressibility.

In practice, it has been demonstrated that a complete "hydro" curve consists of the two straight-line portions but, in addition, contains a "transition" portion between the two straight lines. The transition results from the fact that the soil is inhomogeneous and contains air voids which are either not connected to fluid-filled voids or which have small capillaries and therefore change the solubility of the system.

In order to determine the volume change of partially saturated specimens, as well as other desired constitutive relationships, it is necessary to measure directly the radial dimension changes of the specimens. Having accomplished such measurements, one can treat the data in a manner so that more informative constitutive relationships of the soil are obtained than in the case of the usual test where radial dimension changes are lacking. The capability of varying the radial (or confining) pressure in the triaxial chamber, together with the capability of monitoring radial dimension changes of the specimen, makes it possible to determine the specimen's stress-strain response under a wide variety of stress states. In this test program, four basic types of test were performed. These were:

1. Hydrostatic Compression
2. Triaxial Shear
3. No Lateral Strain (One-Dimensional Compression)
4. Constant Stress Ratio

The Hydrostatic Compression test provides information on the compressibility of the soil under a hydrostatic state of stress ranging upward from atmospheric pressure. The ratio of change in pressure to the change in volume (dp/de) is the bulk modulus, K, of the soil.

As previously indicated, the bulk modulus should have a constant value while the soil is well below the point of saturation. As saturation is approached, the bulk modulus assumes continuously increasing values with increasing hydrostatic pressure. After saturation is complete, the modulus becomes apparently constant.

The Triaxial Shear data, when plotted in the form of $(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$ provide the shear modulus of the soil. For elastic soil behavior, the shear modulus, G, is numerically equal to one-half of the slope of the $(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$ curve. Thus, the measurement of radial deformation during the triaxial test allows the determination of both the Young's modulus, E, as well as the shear modulus.

The No-Lateral-Strain (K^o) test provides information comparable to that of the One-Dimensional Compression test. The constrained modulus, M, is defined as the slope of the σ_a vs ϵ_a curve as determined for the condition of no lateral strain.

The Constant Stress Ratio test provides deformational information for stress states between the two limits $\sigma_r/\sigma_a = 0$ and $\sigma_r/\sigma_a = 1$. The limit $\sigma_r/\sigma_a = 0$ is the triaxial test which provides the usual shear modulus and the limit $\sigma_r/\sigma_a = 1$ is the hydrostatic compression test which provides the bulk modulus.

The shear strength of a soil is generally represented in the form of a Mohr diagram. Two parameters, C and ϕ, are sufficient to describe the strength if the confining pressures are low; however, in the case of confinement which varies from zero up to 10,000, the envelope is not a straight line. For such cases, it is necessary to have the entire strength envelope in order to determine the soil strength for a given condition.

While the soil is only partially saturated, the strength envelope will be inclined at an angle to the horizontal greater than zero. After the soil becomes saturated, the envelope becomes horizontal, for practical purposes, since the stresses are assumed to be carried by neutral stress.

McCormick Ranch Sand

The "hydro" curve (Figure 22) closely approximates a straight line up to a pressure of about 400 psi and to a volumetric strain between 2.5% to 3.0%. A transition curve then exists between 400 psi and approximately 800 psi with only a slight increase in strain. At hydrostatic pressures above about 800 psi, the slope apparently becomes constant once again.

Due to the limitations of the lateral deformeter, it is unlikely that a modulus greater than approximately 3×10^5 psi can be established with any predictable degree of confidence. As a result, the p vs $\Delta V/V_o$ curves past the saturation point should be used primarily in a qualitative sense. In this case, it is apparent that the bulk modulus of the saturated soil is considerably higher than that of water alone.

Typical plots for the Triaxial Test shear stage results for the sand are shown in Figure 23 through Figure 25. These plots show "averaged" curves which were constructed by utilizing all results from tests of a like nature and determining the numerical average strain for a given stress value. Some engineering judgment was exercised in this process and certain test results were not used when they contained apparent discrepancies.

These curves exhibit no totally unexpected behavior even to the maximum confining pressure utilized. The individual curves show increasing deviator stress to either a maximum value or to a very slowly

increasing value as deviator strain increases. The stiffness of the soil increases with increasing confining pressure and consequently, the shear modulus will exhibit an increase with confining pressure. It appears that the shear modulus reaches either a maximum or a slowly increasing value after full saturation has occurred.

Cyclic loading (Figure 24) interrupts the normal pattern of stress vs strain in that "hysteresis loops" are formed; however, the curve, after cyclic loading is complete, is apparently a continuation of the portion of the curve prior to cyclic loading. This is compatible with observed behavior of soils under cyclic loading at low confining pressures. (Figure 24 is for a single test since cycling of load was not accomplished at identical values in all tests and "averaging" is not possible.)

The $(\sigma_a - \sigma_r)$ vs ϵ_r curves show that there is an increase in the diameter of the specimen with increasing axial load during the shear stage regardless of the initial confining pressure. Such behavior would be expected even at confining pressures less than those necessary to produce saturation.

The "Constant Stress Ratio" test results are shown in Figure 26 and Figure 27. The $(\sigma_a \quad)$ vs $(\epsilon_a - \epsilon_r)$ curves are similar to those for standard triaxial tests in that there is an approximately straight-line initial portion followed by a curving transition and then a failure, or peak value of deviator stress.

The σ_r vs ϵ_r curves are an unusual type of presentation since lateral deformation is not normally measured. The diameter strain is seen to decrease, at first, with increasing confining pressure and then to increase. The significance of this behavior is not yet clear, but it is probably related to the compression and shear phases of a conventional triaxial test.

The Mohr diagram is shown in Figure 28. The envelope appears to be slightly concave downward up to 800-psi confining pressure. This portion of the envelope can be approximated by a straight line with a friction angle ϕ of about 11 deg. Between 800 psi and 1200 psi the curvature becomes more pronounced and the envelope becomes essentially horizontal at 1200 psi and remains so up to 10,000 psi. No "cohesion" intercept is shown, since the minimum confining pressure was relatively high and the slope of the envelope could change considerably for lower confining pressures.

Watching Hill Clay

The "hydro" curve (Figure 29) approximates a straight line up to a pressure of about 200 psi and to a volumetric strain of approximately 10%. A transition curve then exists between 200 psi and approximately 800 psi with only a slight increase in strain. At hydrostatic pressures above about 800 psi, the slope apparently becomes constant once again.

The same comments regarding the bulk modulus apply to this soil as were indicated for the McCormick Ranch Sand. The large amount of volumetric strain prior to saturation for this soil is due to the initial high void ratio.

The general shapes of the specimens after testing are shown in Figure 30 and Figure 31. The specimen in Figure 32 has been subjected to hydrostatic compression only, and the typical decreased diameter can be seen to vary from the central portion to the ends of the specimen. The ends undergo a negligible amount of deformation. The specimen in Figure 31 was subjected to hydrostatic compression of 3200 psi and then sheared in a standard triaxial test. This particular specimen was strained to approximately 28% axial strain. The ends still remain undeformed while the specimen bulges fairly uniformly over the central portion.

These photographs, as well as the other recorded data, show rather clearly that there is an appreciable end-cap effect on the radial deformation of the specimens. There may also be an effect on the axial deformation. As a consequence of the restraint, the volumetric changes are influenced, which introduces an error of unknown magnitude into predictions of bulk modulus and other deformational moduli. It appears that a definite need exists for study of the end-cap effects at high confining pressure.

Typical results of the Triaxial and Constant Stress Ratio tests are shown in Figure 32 through Figure 40. The general shapes of the curves are similar to those of the McCormick Ranch Sand. The lower density of the silt is exemplified by the $(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$ curves where the slopes are flatter (i.e., lower shear modulus) than for the sand. The Triaxial test results (Figure 32 and Figure 33) are shown to two different scales in order to better illustrate both the low strain and the high strain behavior.

A set of curves (Figures 36 through 39) shows the deformational characteristics of the clay in the Constant Stress Ratio tests. Figures 36, 37, 38, and 39 show the behavior at stress ratios of 0.4, 0.6, and 0.8 for various initial confining pressures. In general, the initial slopes of the curves decrease with increasing stress ratios for a given initial confining pressure; however, the difference is not too great, and there is no well-defined relation. The loading path, therefore, does not greatly influence the deformational behavior when presented in these terms.

A combined, or "averaged," set of curves is shown in Figure 40 to illustrate the effect of initial confinement for a given stress ratio loading path. The behavior is quite similar to that in conventional triaxial compression, with the slope of the curves increasing with increasing initial confinement and tending toward a constant value after complete saturation under initial confining pressure.

The "No-Lateral-Strain" test results are typified by Figure 41 and Figure 42.

The Mohr diagram for the clay is shown in Figure 43. The envelope can be approximated by a straight line up to approximately 800 psi at an angle of about 4 deg. At confining pressures greater than 800 psi, the envelope is essentially horizontal up to 10,000 psi.

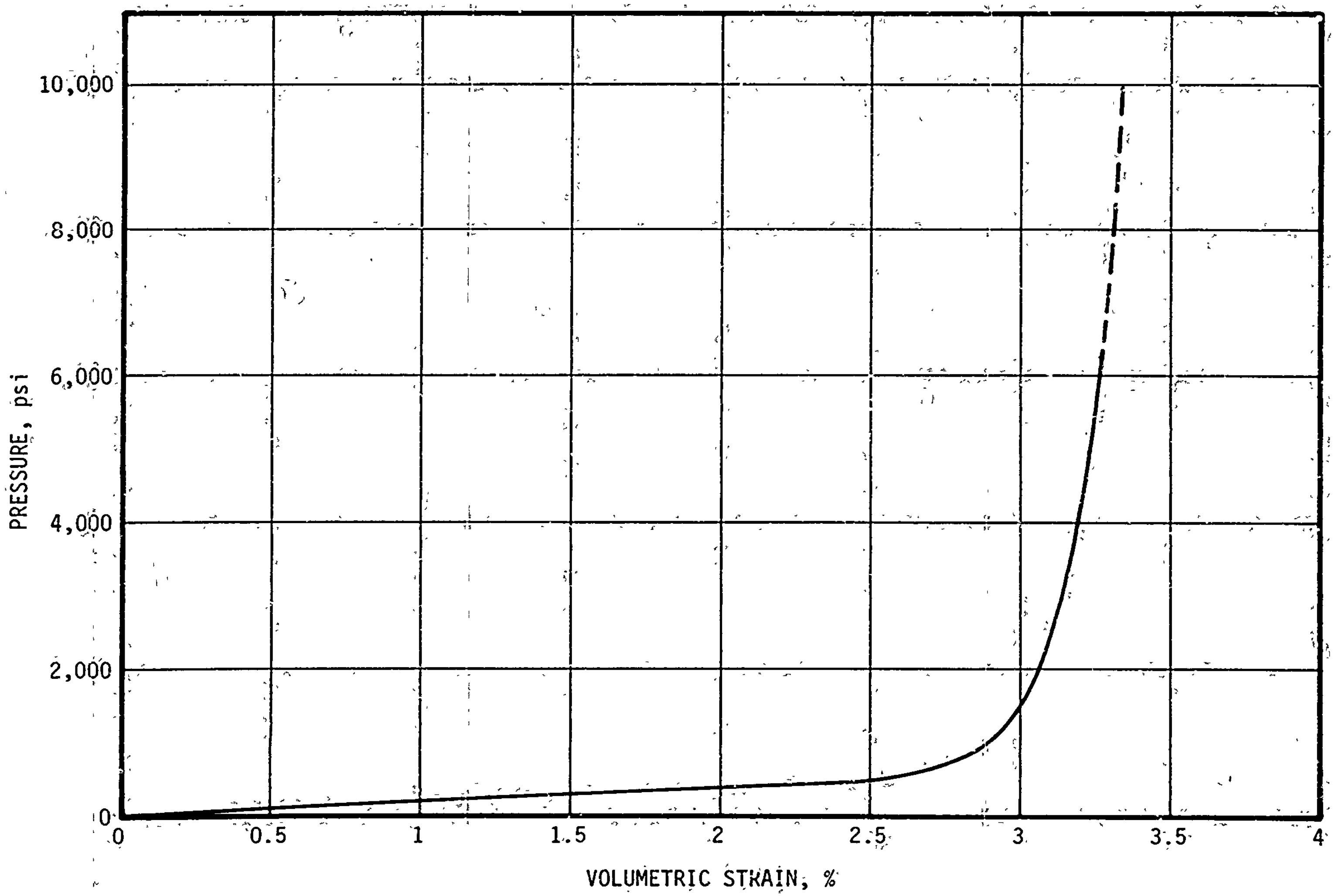


Figure 22. McCormick Ranch Sand; Hydrostatic Compression Curve

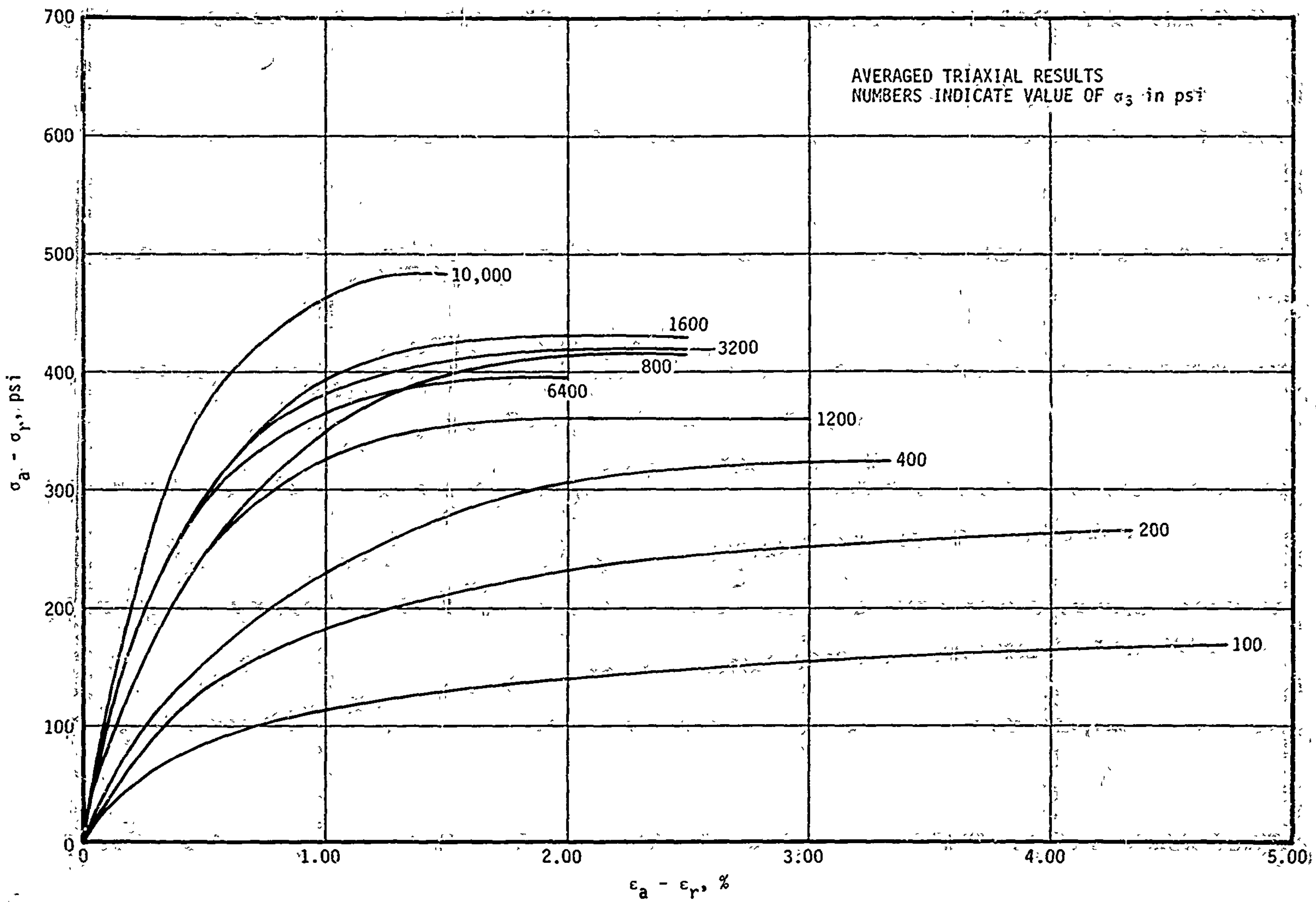


Figure 23. McCormick Ranch Sand; Triaxial Test Results; $(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$

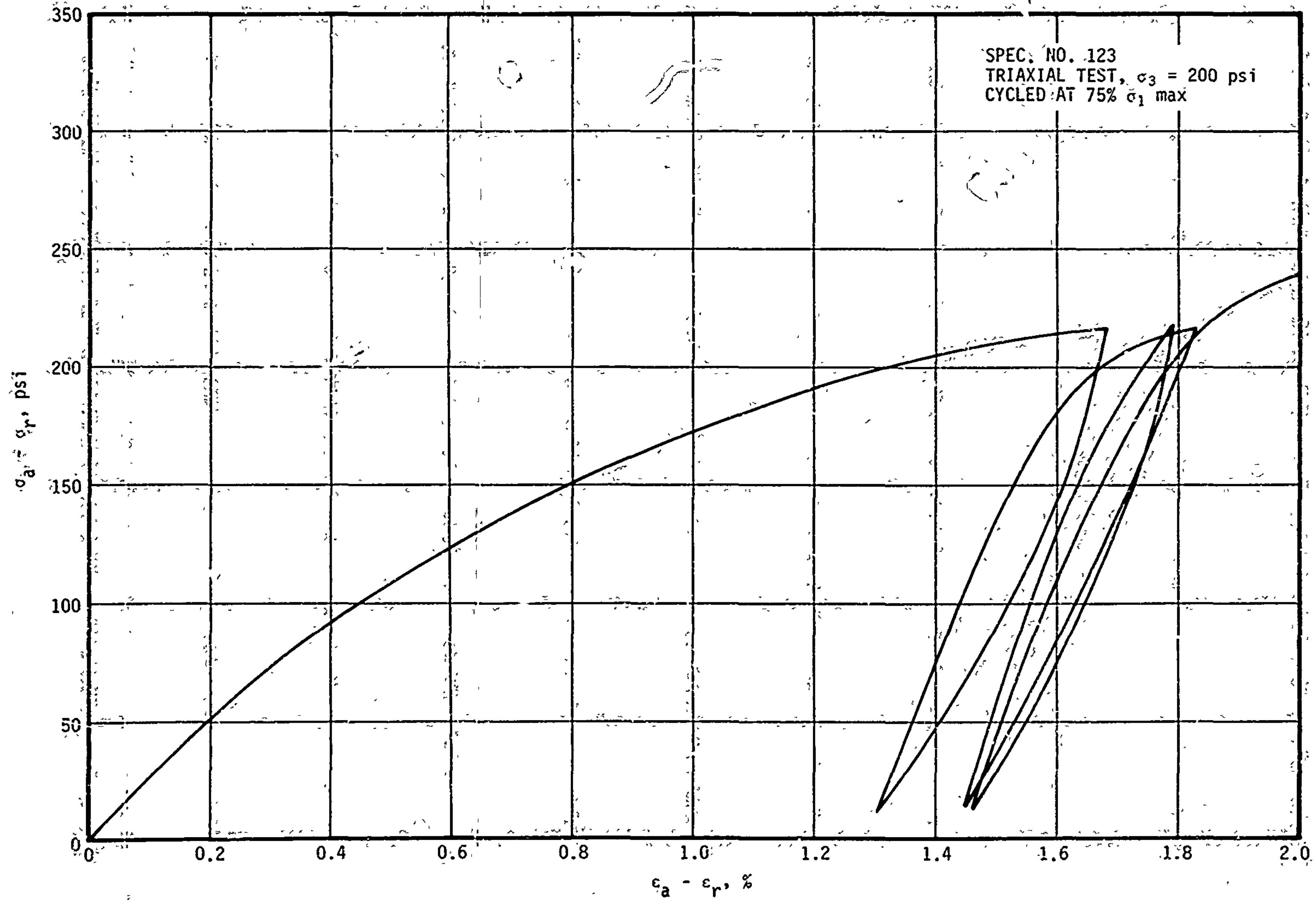


Figure 24. McCormick Ranch Sand; Cyclic Triaxial Test; σ_3 = 200 psi; $(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$

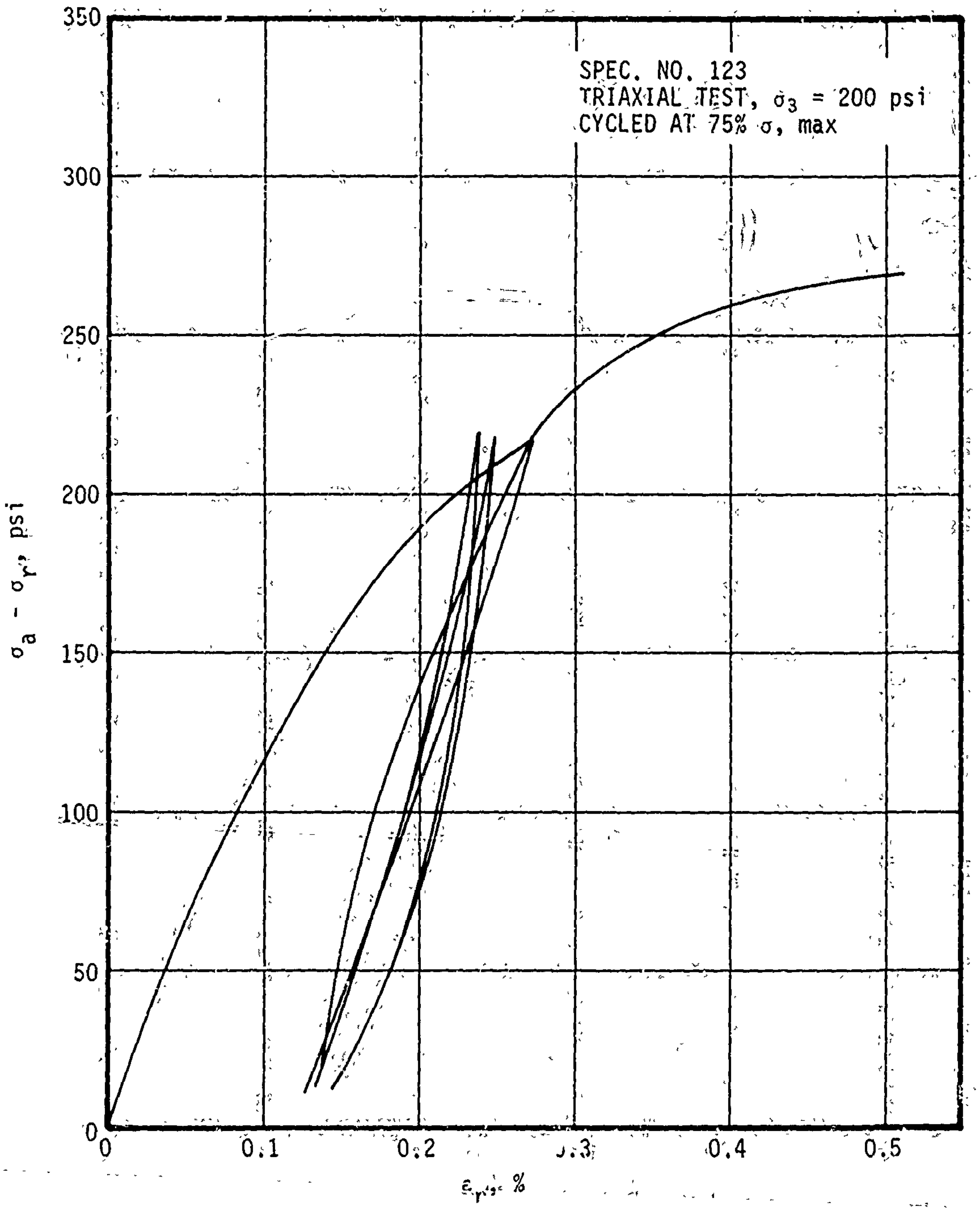


Figure 25. McCormick Ranch Sand; Cyclic Triaxial Test; σ_3 = 200 psi; $(\sigma_a - \sigma_r)$ vs ϵ_r

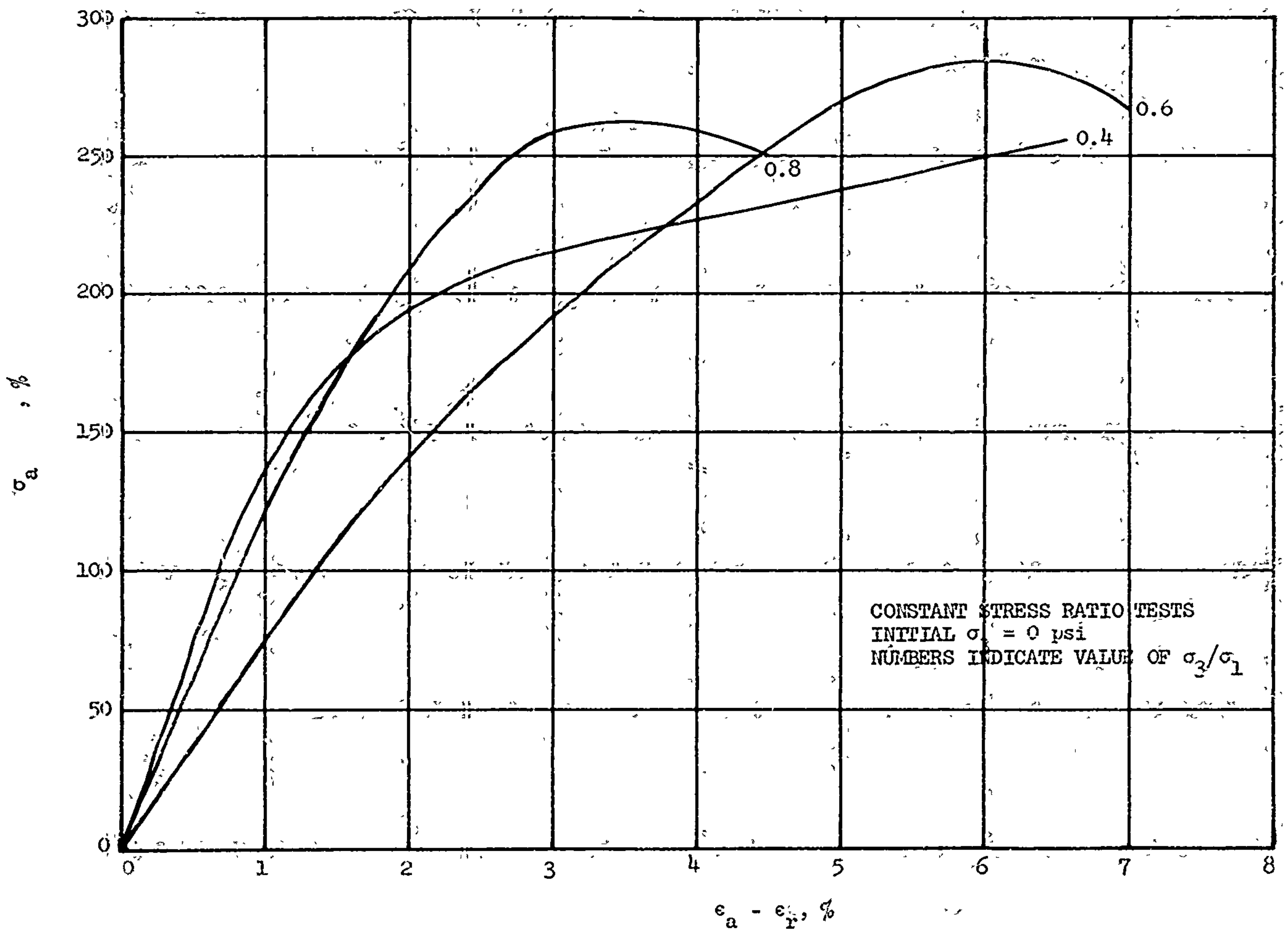


Figure 26. McCormick Ranch Sand; Constant Stress Ratio Results; Initial Confining Pressure = 0 psi; (σ_a) vs ($\epsilon_a - \epsilon_r$)

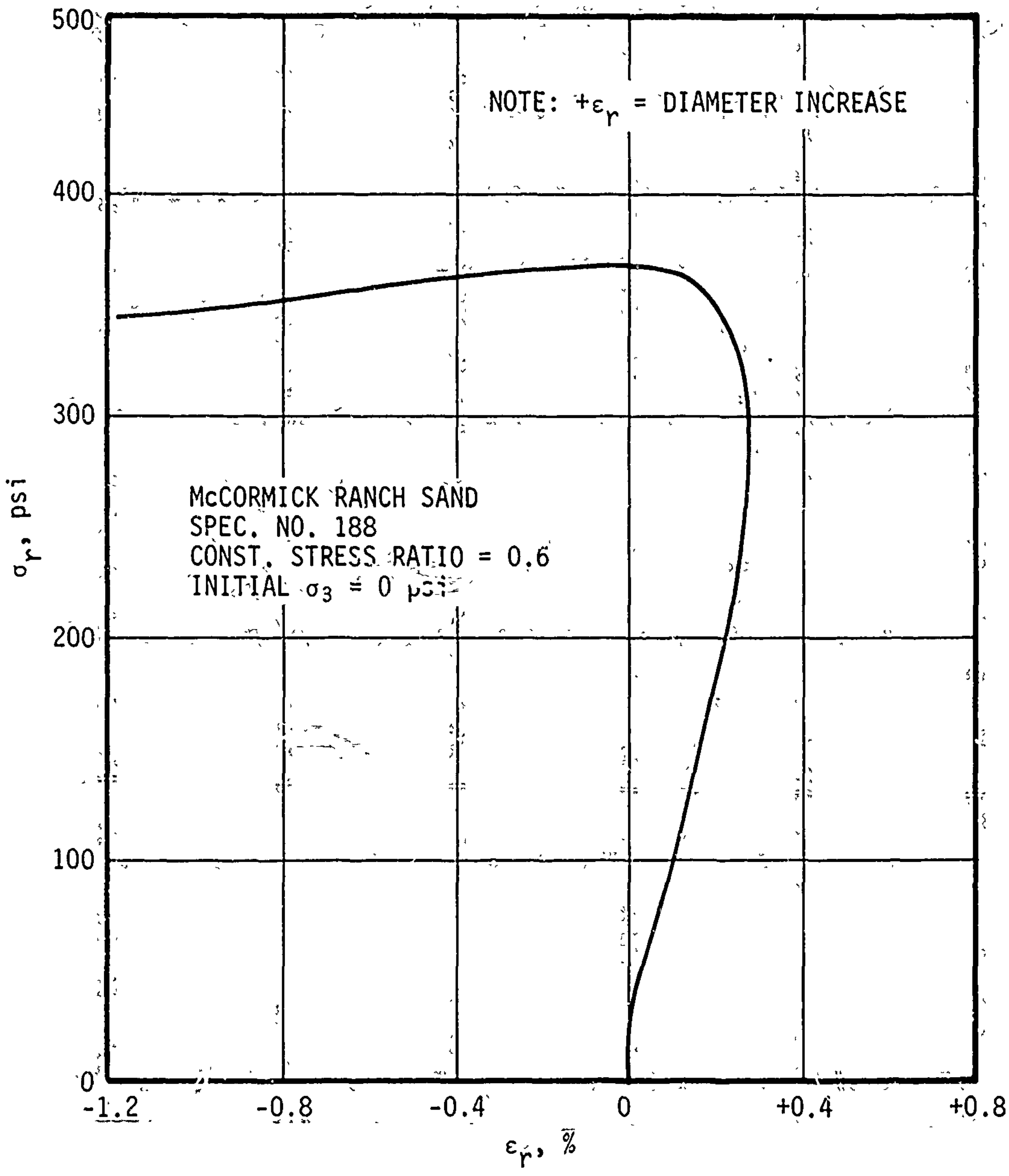


Figure 27. McCormick Ranch Sand; Constant Stress Ratio = 0.6; Initial Confining Pressure = 0 psi; σ_r vs ϵ_r

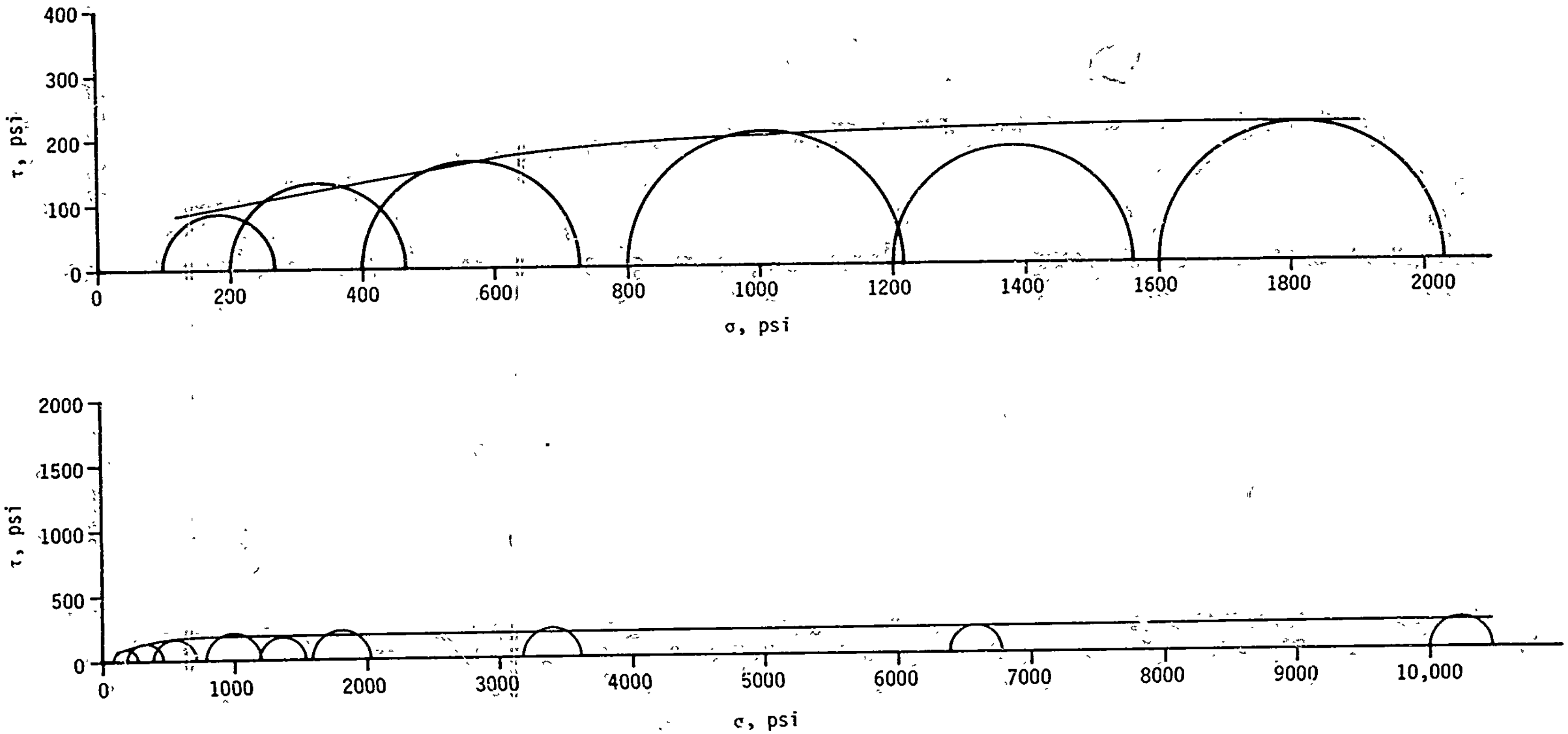


Figure 28. McCormick Ranch Sand; Mohr Diagram

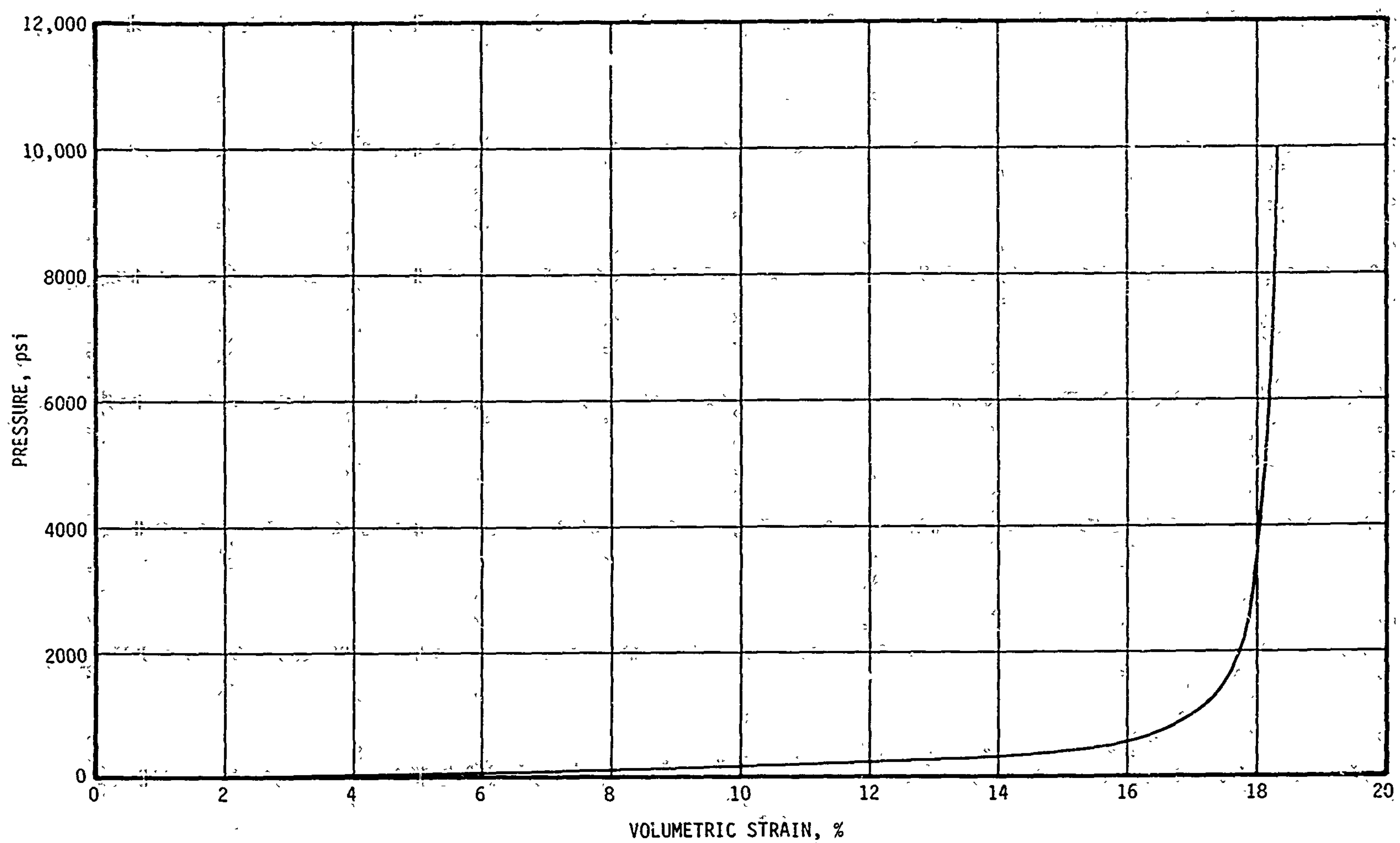


Figure 29. Watching Hill Clay; Hydrostatic Compression Curve

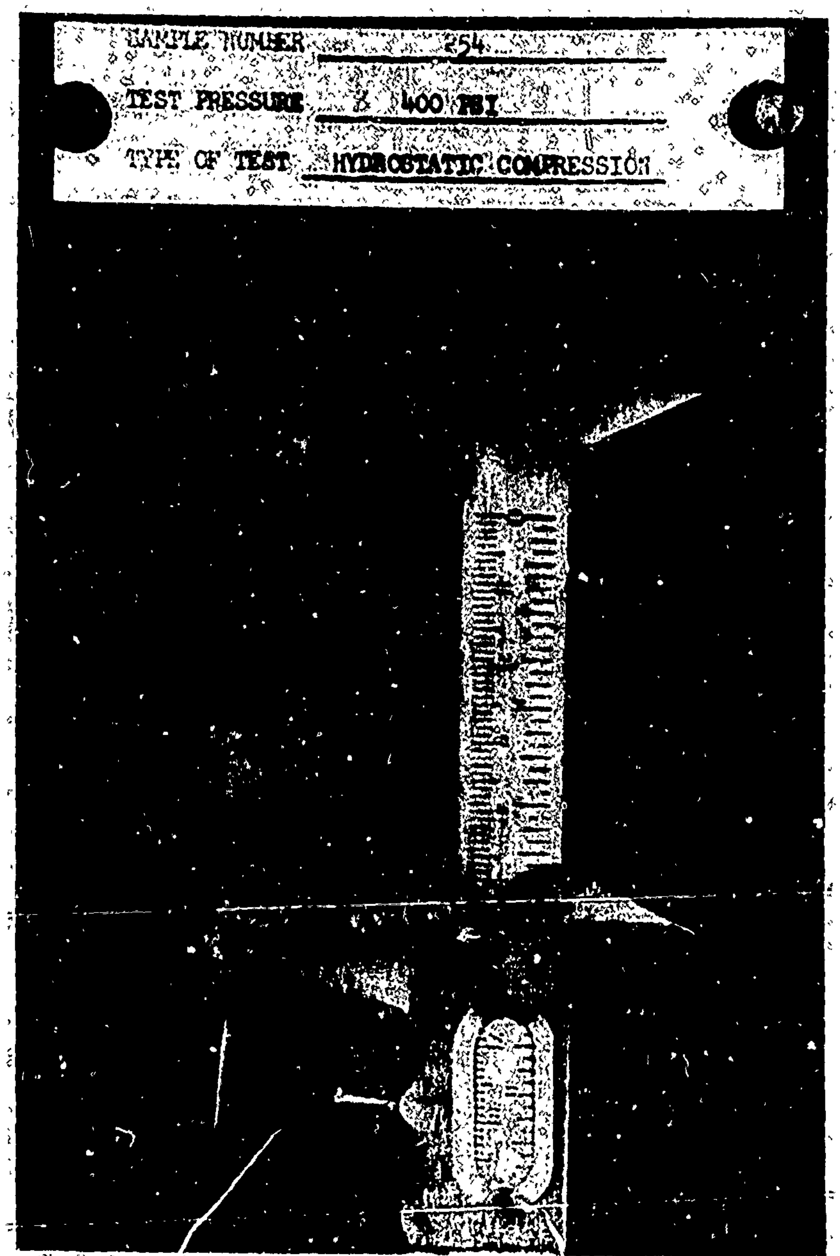


Figure 30. Clay Specimen Subjected to 400-psi Hydrostatic Compression

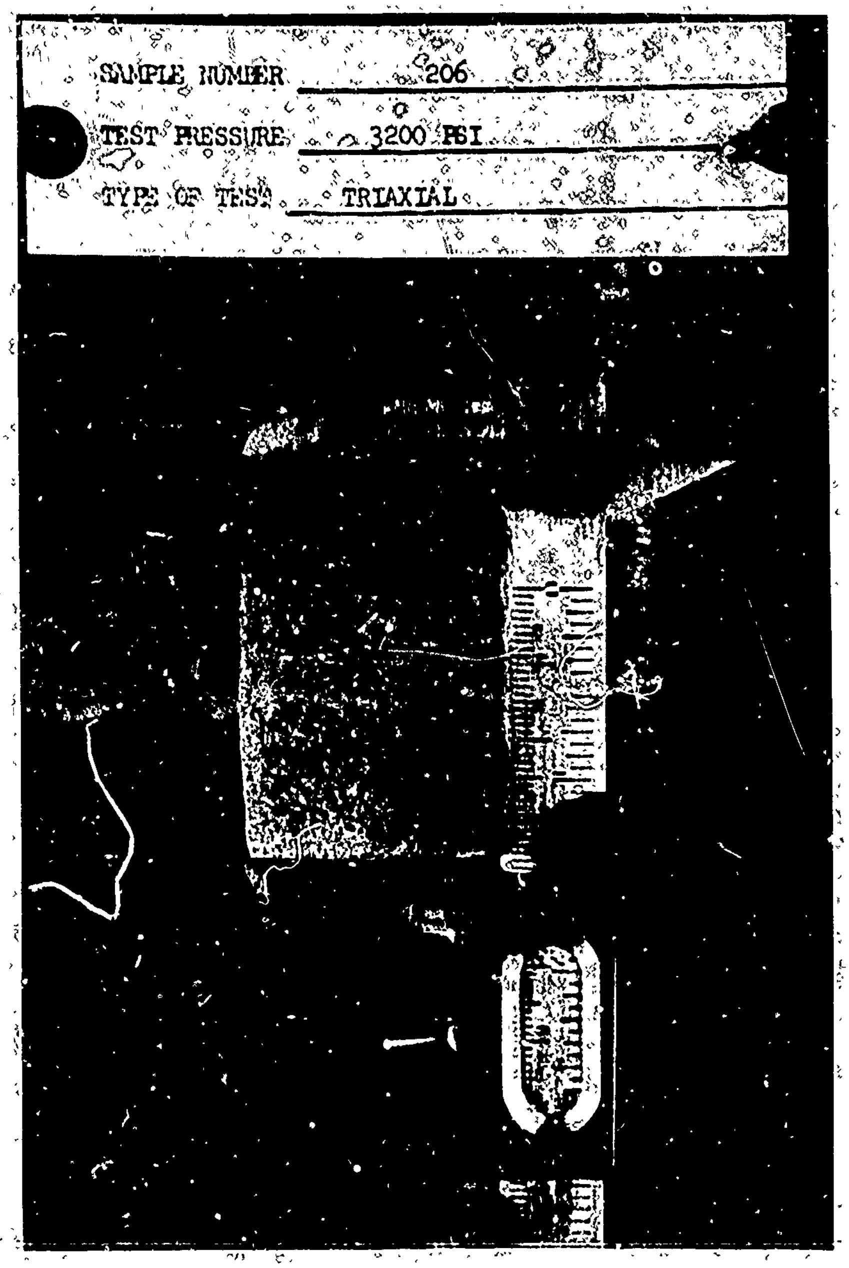


Figure 31. Clay Specimen Subjected to 3200-psi Hydrostatic Compression

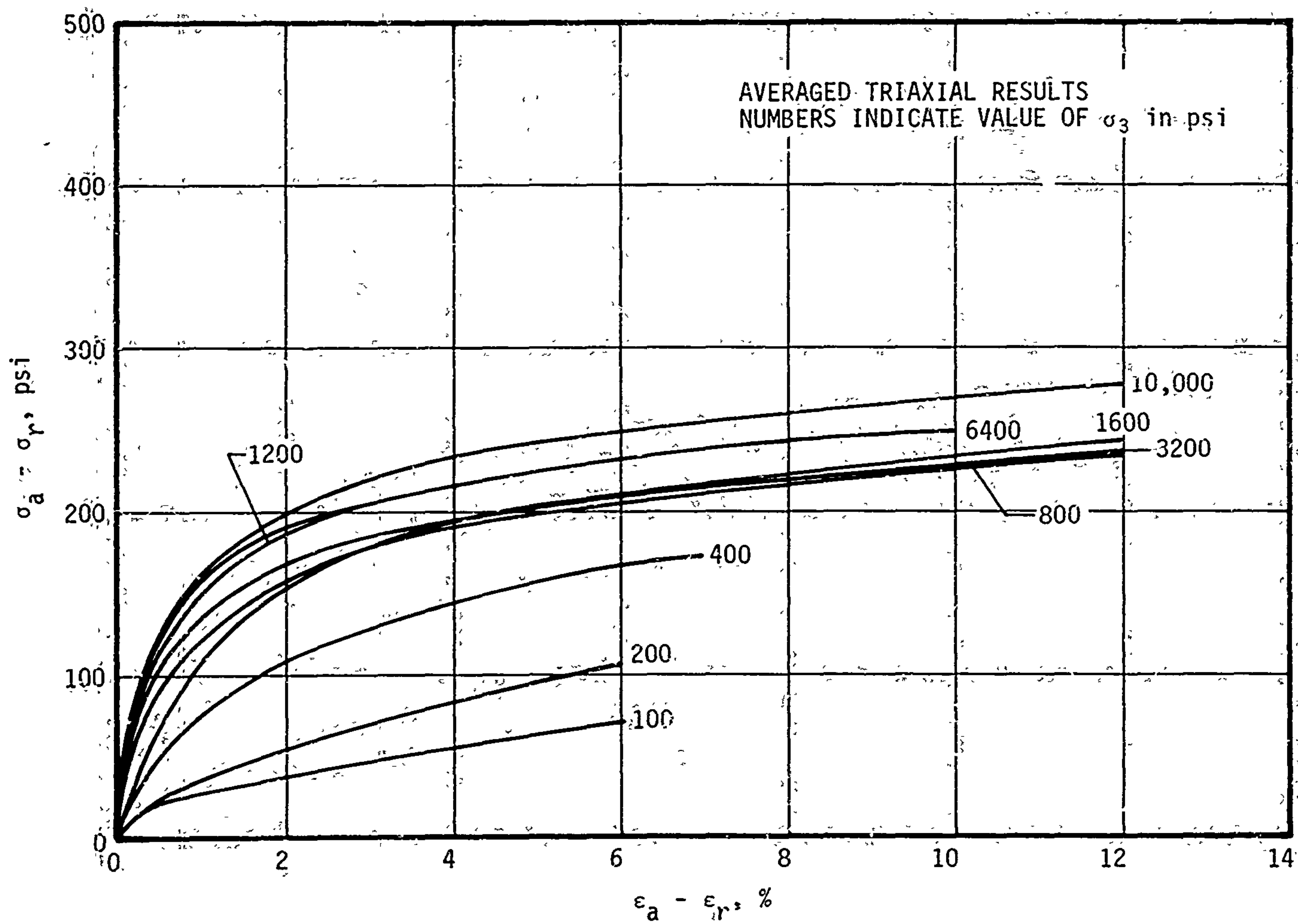


Figure 32. Wathcing Hill Clay; Triaxial Test Results; $(\sigma_a-\sigma_r)$ vs $(\epsilon_a-\epsilon_r)$

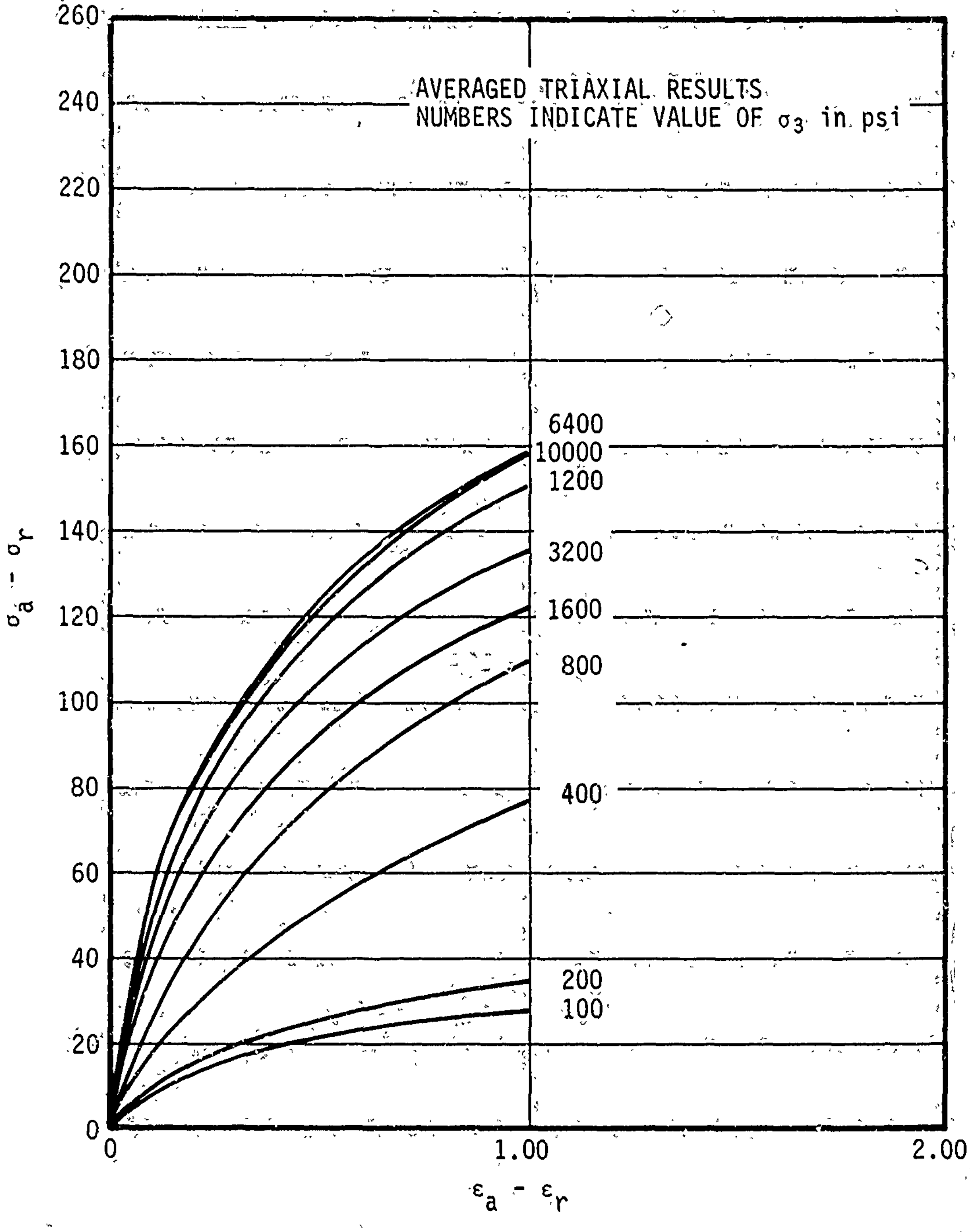


Figure 33. Watching Hill Clay; Triaxial Test Results; $(\sigma_a - \sigma_r)$ vs $(\epsilon_a - \epsilon_r)$; Expanded Scale

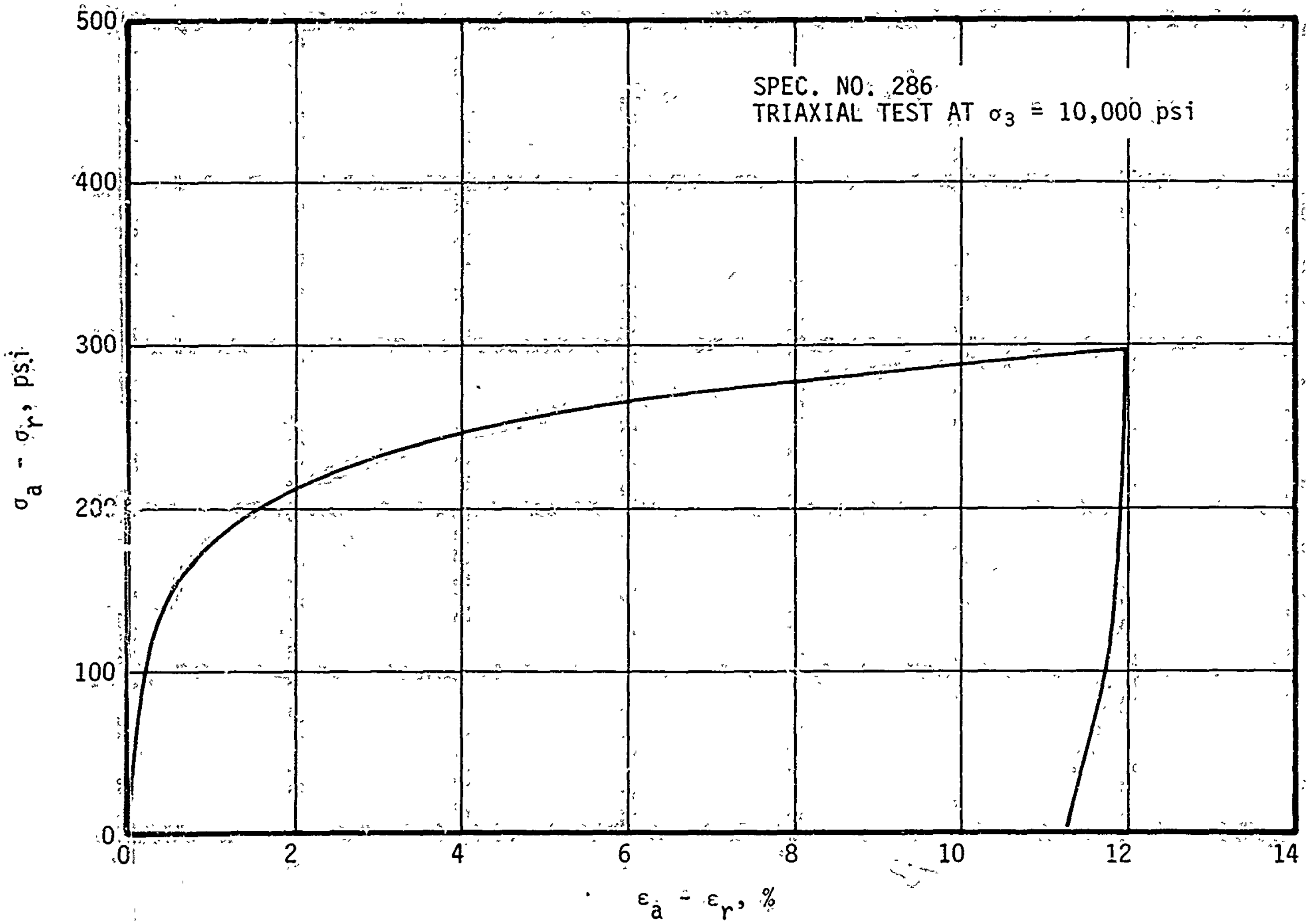


Figure 34. Watching Hill Clay; Triaxial Test; σ_3 = 10,000 psi; $(\sigma_a - \sigma_r)$ vs $(\varepsilon_a - \varepsilon_r)$

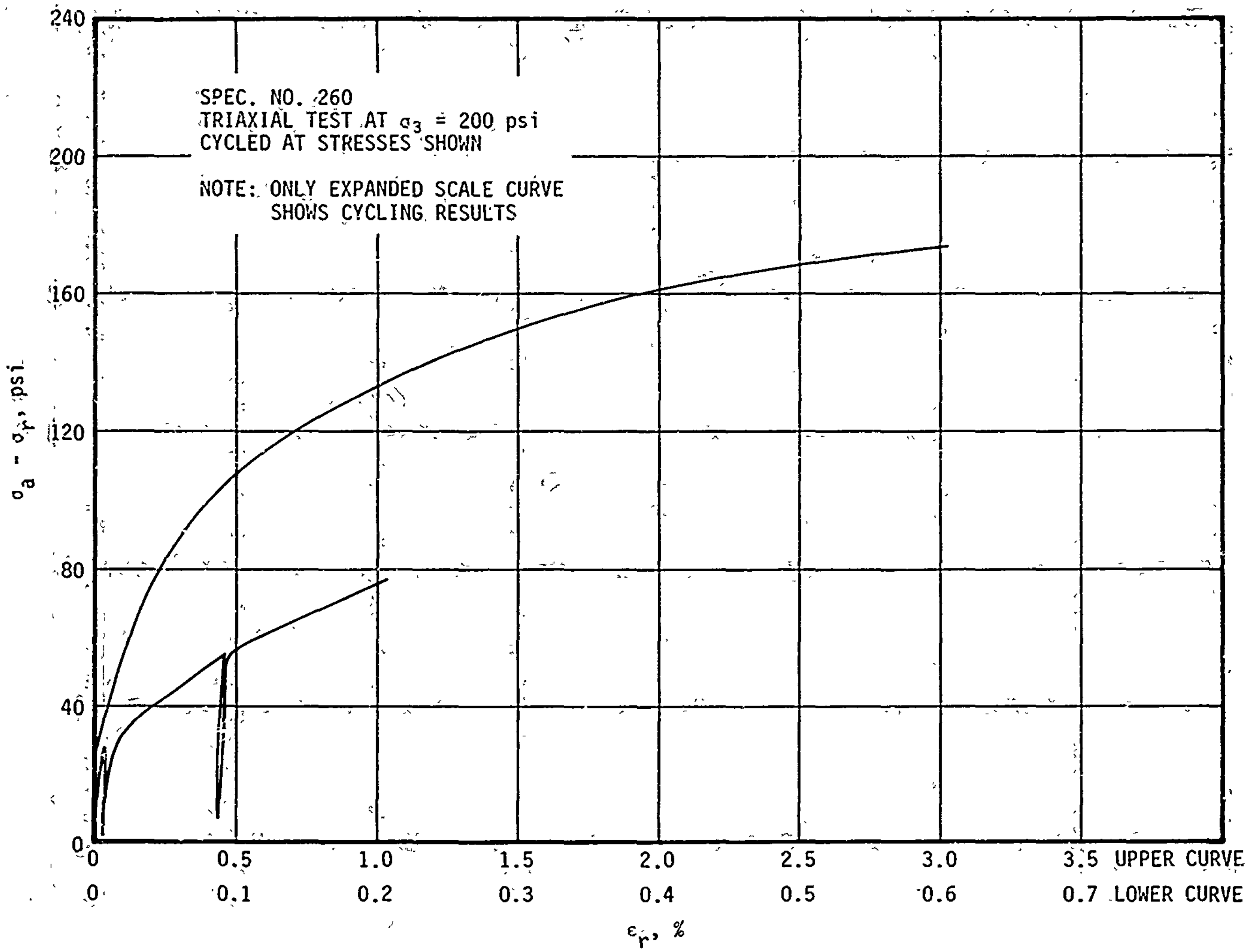


Figure 35. Wathcing Hill Clay; Cyclic Triaxial Test; σ_3 = 200 psi; $(\sigma_a - \sigma_r)$ vs ϵ_r

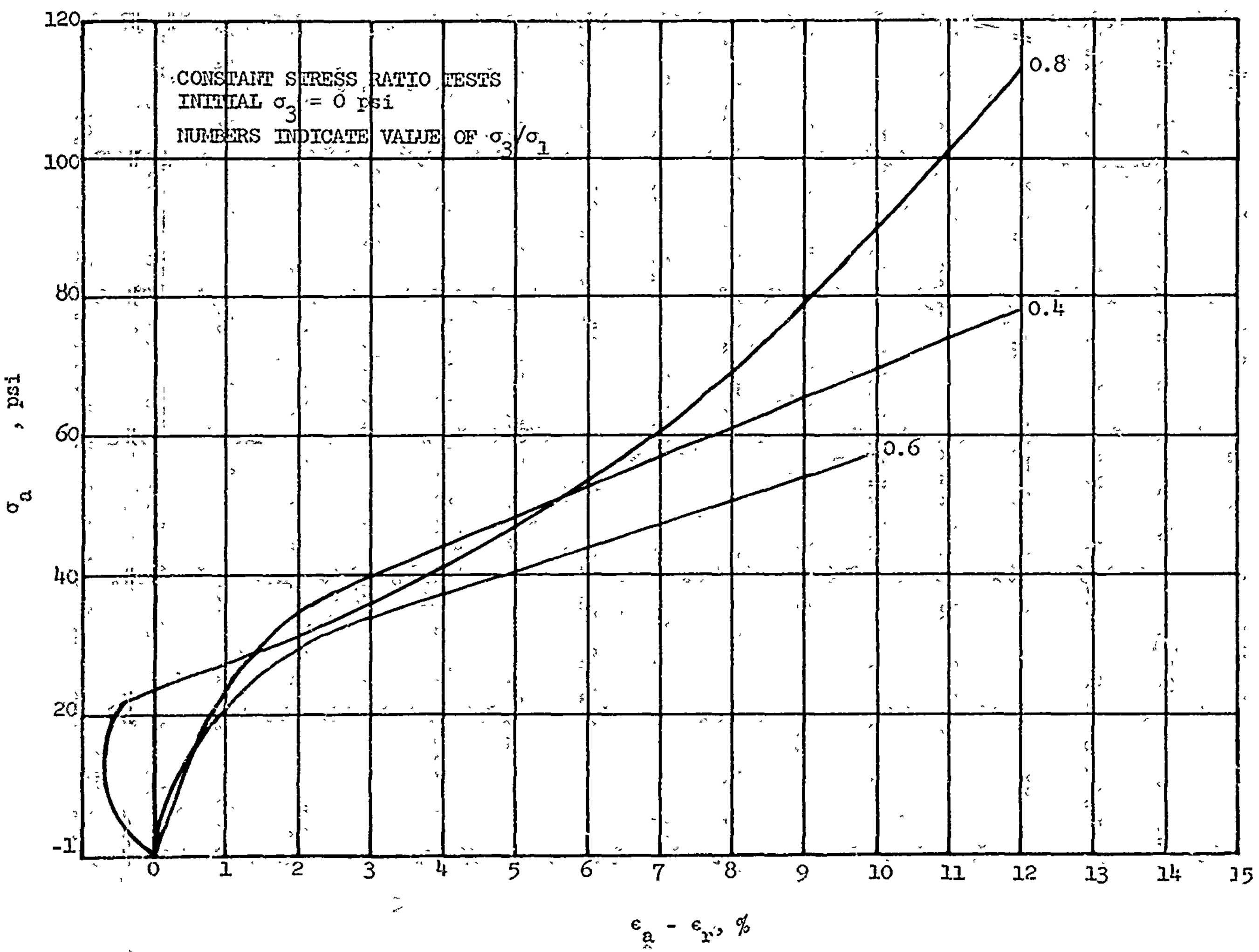


Figure 36. Watching Hill Clay; Constant Stress Ratio Results; Initial Confining Pressure = 0; (σ_a) vs (ϵ_a-ϵ_r)

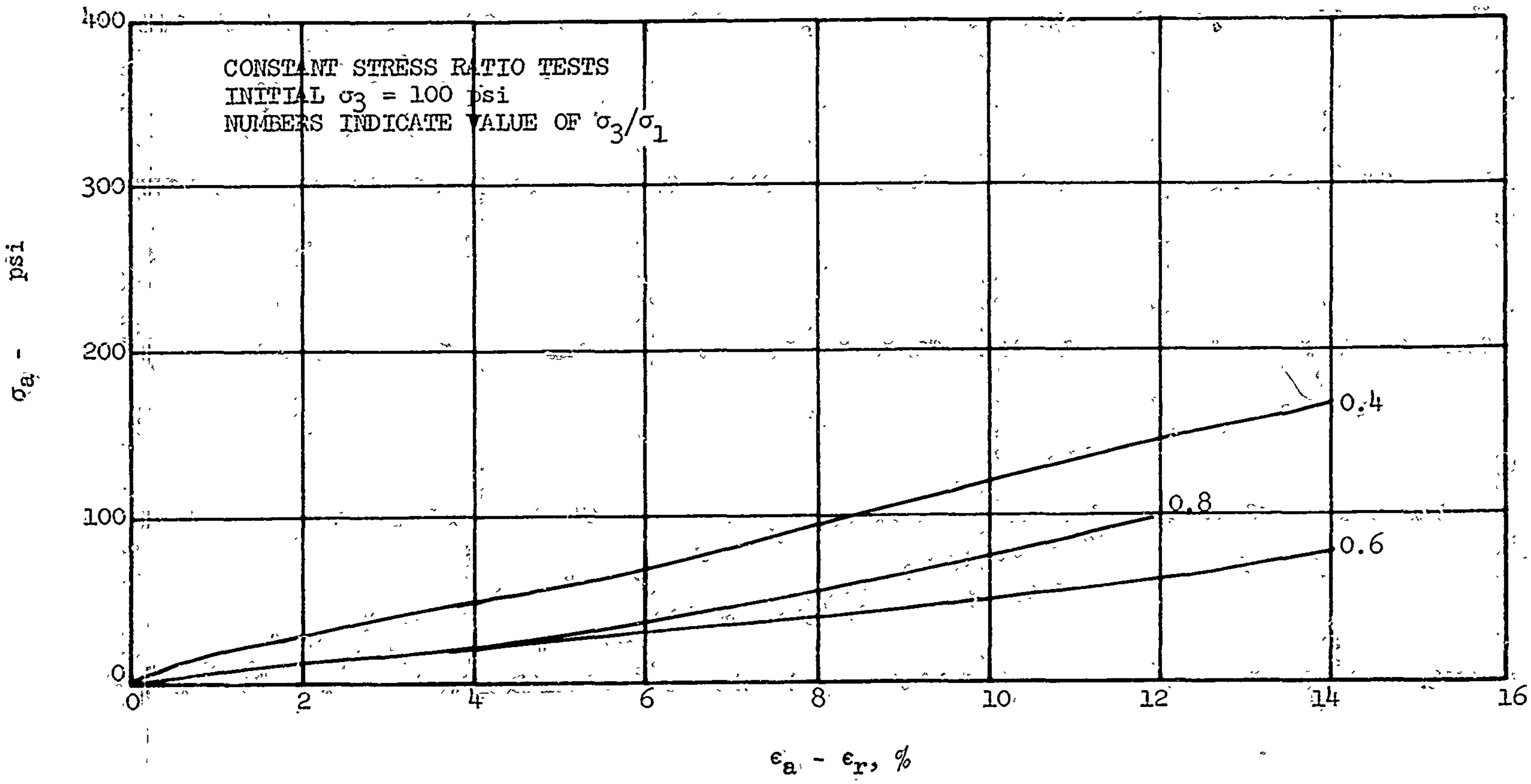


Figure 37. Watching Hill Clay; Constant Stress Ratio Results; Initial Confining Pressure = 100 psi; (σ_a) vs (ϵ_a-ϵ_r)

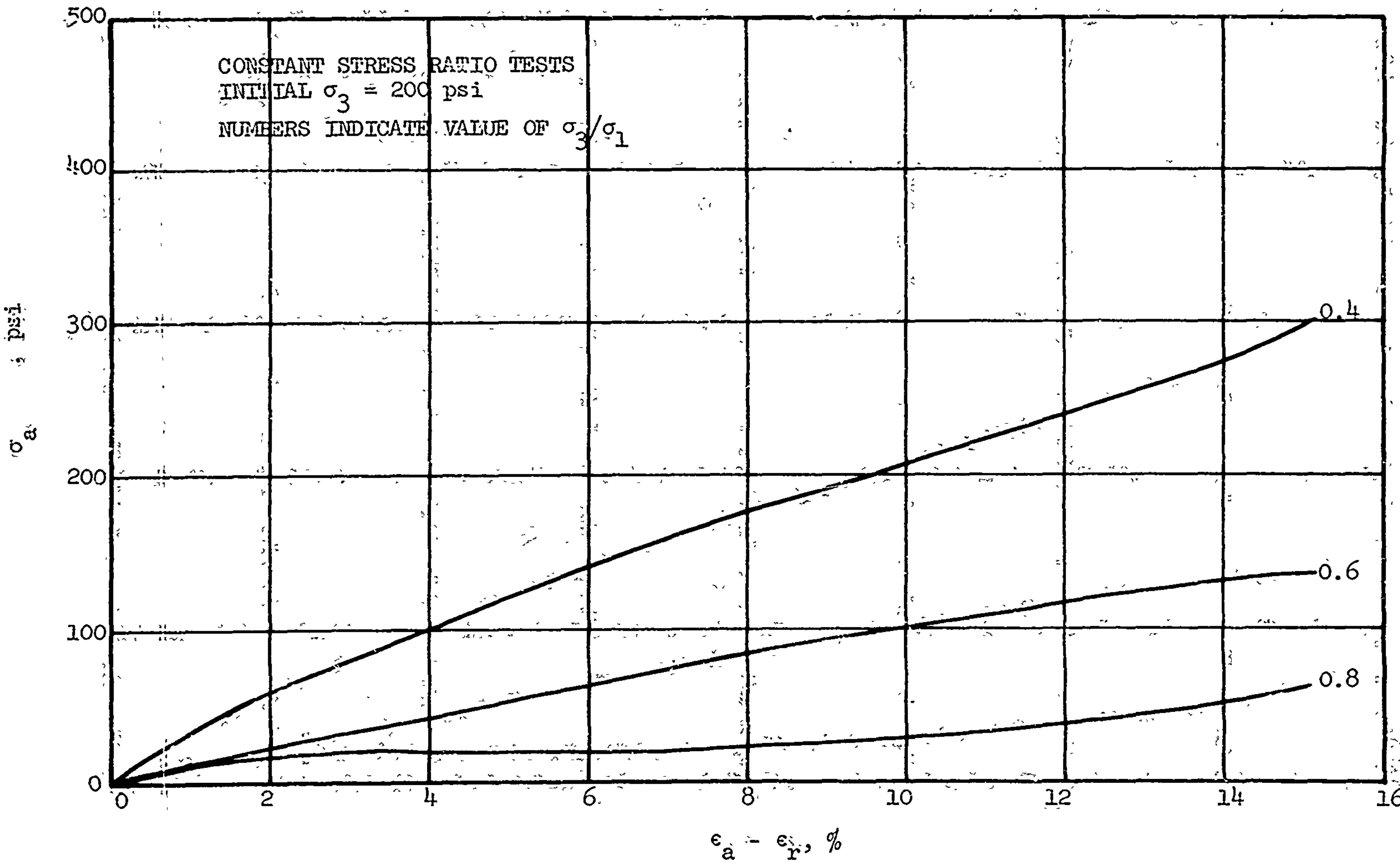


Figure 38. Watching Hill Clay; Constant Stress Ratio Results; Initial Confining Pressure = 200 psi; (σ_a) vs (ϵ_a-ϵ_r)

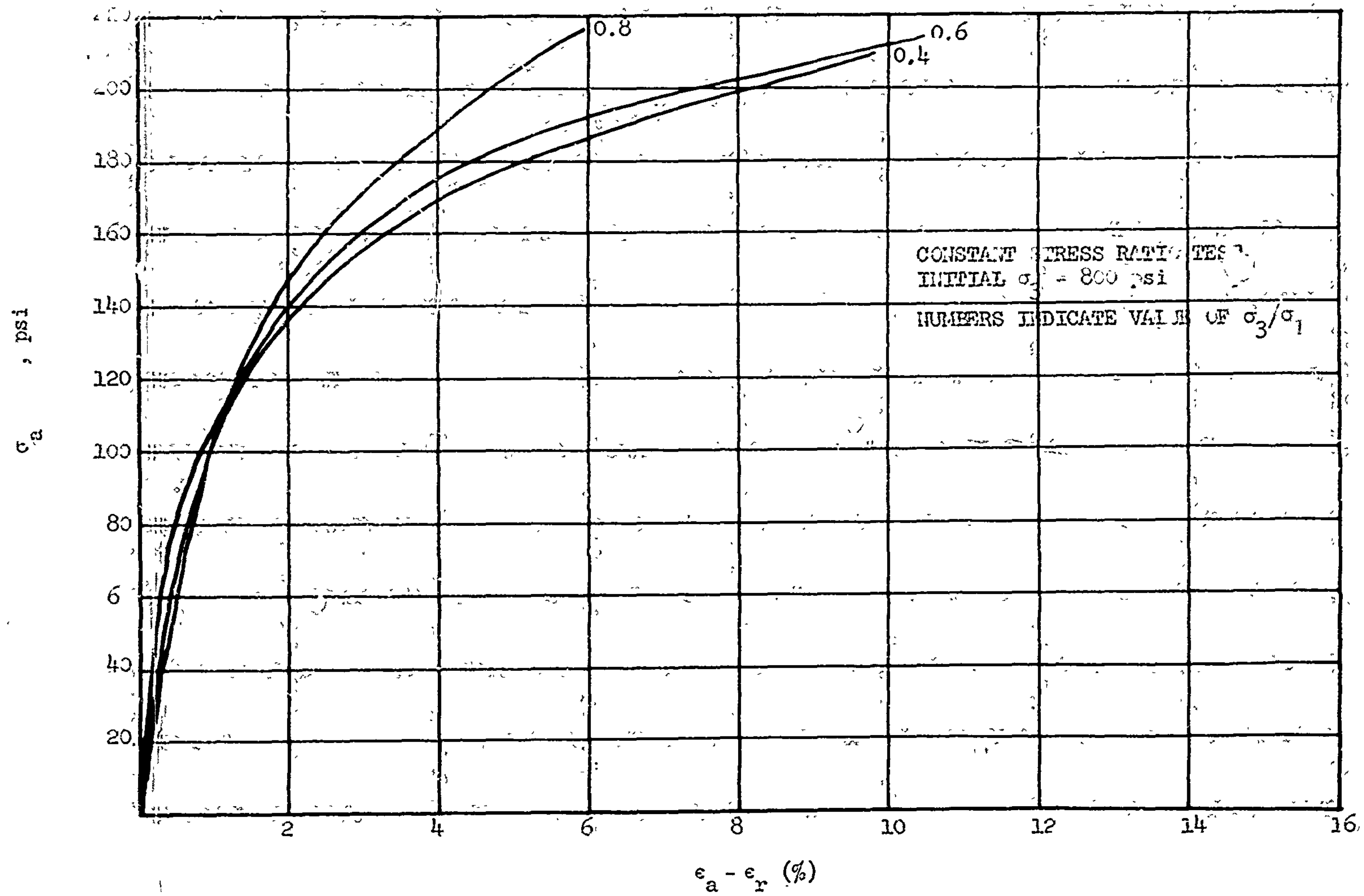


Figure 39. Watching Hill Clay; Constant Stress Ratio Results;
Initial Confining Pressure = 800 psi; (σ_r) vs (c_a-ϵ_r)

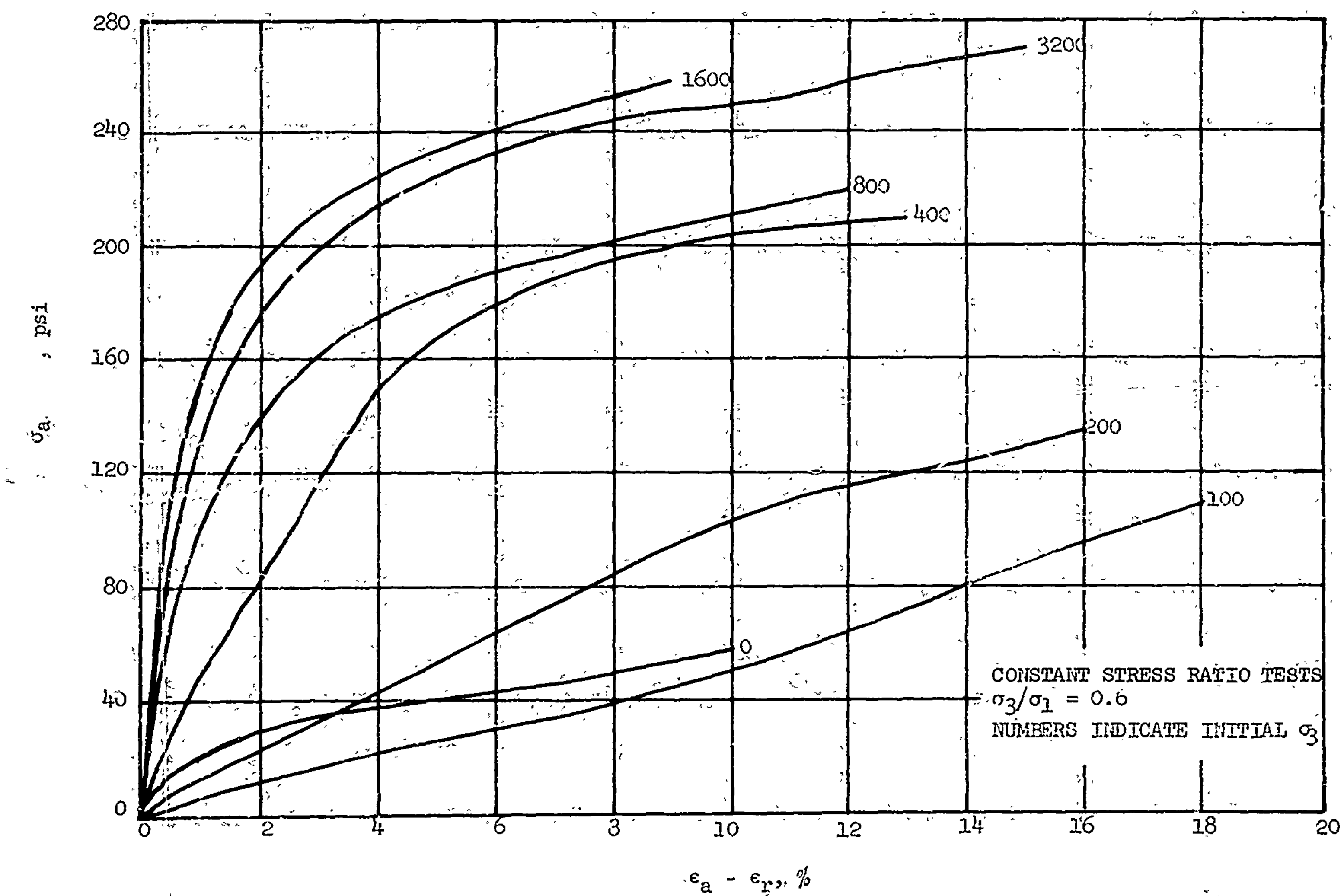


Figure 40. Watching Hill Clay; Constant Stress Ratio - 0.6; Various Initial Confining Pressures; (σ_a) vs ($\epsilon_a - \epsilon_r$)

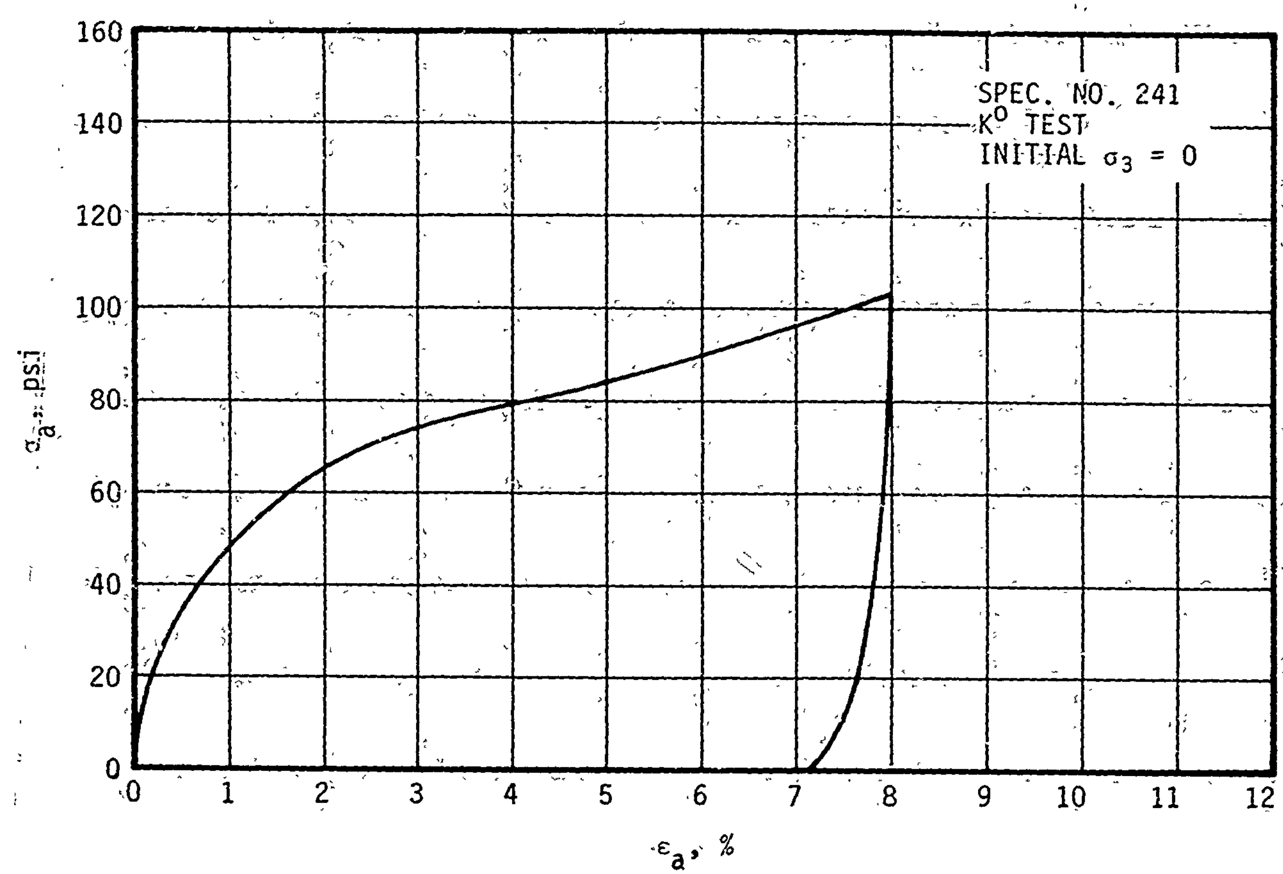


Figure 41. Watching Hill Clay; No-Lateral-Strain Test; Initial Confining Pressure = 0; σ_a vs ε_a

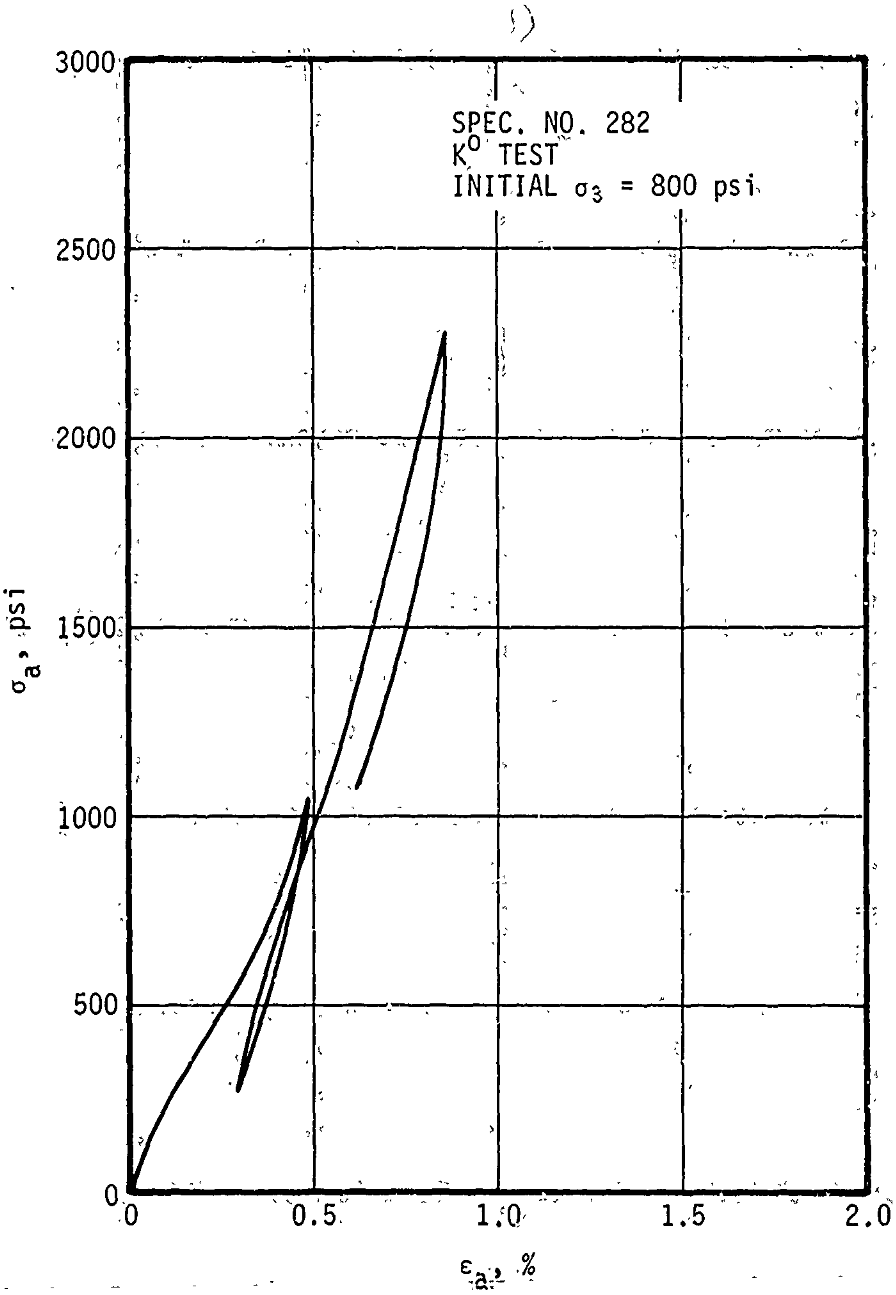


Figure 42. Watching Hill Clay; No-Lateral-Strain Test; Initial Confining Pressure = 800 psi; σ_a vs ϵ_a

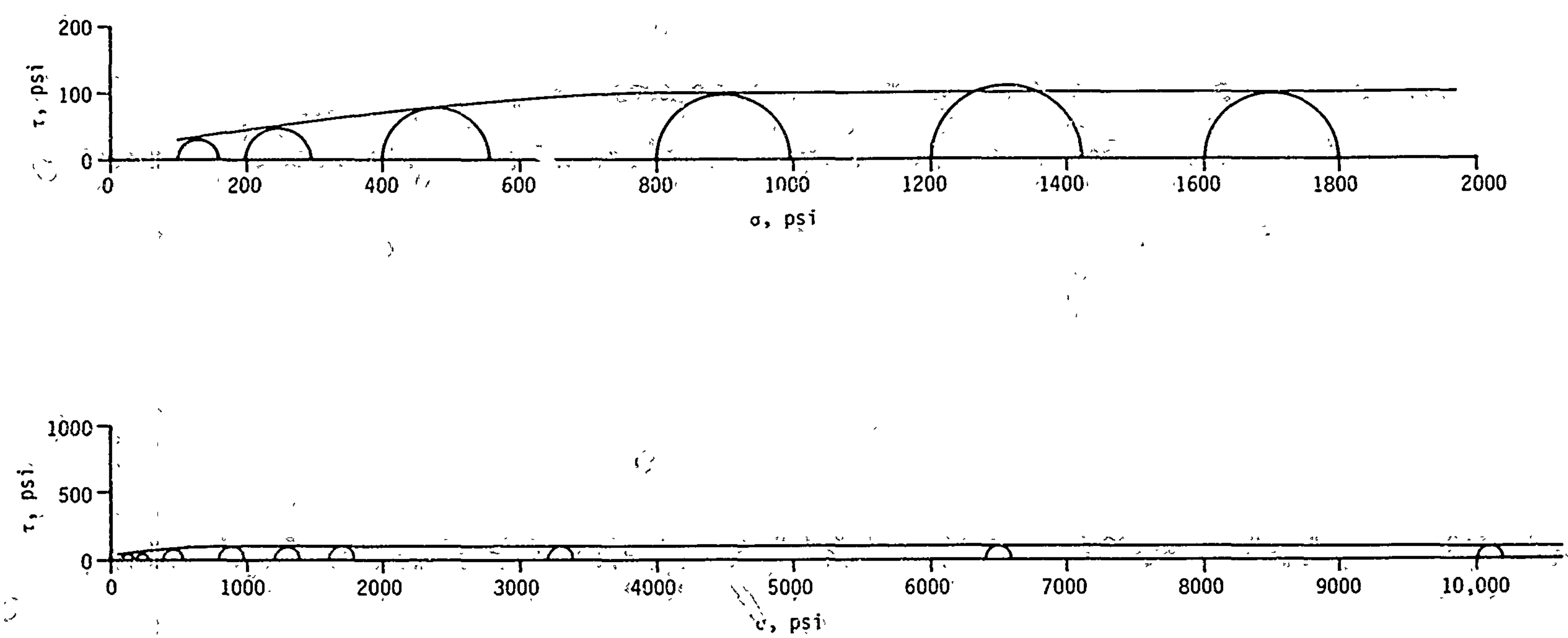


Figure 43. Watching Hill Clay; Mohr Diagram

CHAPTER VII

RECOMMENDATIONS FOR FURTHER STUDY

The work performed during this study was of a nature which had not previously been attempted. The results obtained are quite interesting in themselves and may be used in predictions of the behavior of earth masses. The accuracy of the predictions will depend to a considerable extent, however, upon the differences in physical properties (density, moisture content, etc.) between the laboratory soils and those in situ. Considerable differences in physical properties exist in a given deposit, both in vertical as well as in horizontal directions. This variation in the soil indicates the need for knowledge of the range of variation of the mechanical properties and deformational characteristics of the material. In order to determine this range of variation, it will be necessary to perform a systematic study which includes variations of the soil physical properties, e.g., densities and water contents from the minimum expected, various gradations, etc.

Two soils were studied. These were relatively weak and particulate in nature. Other soils and rock should be utilized in order to obtain specific values for materials actually surrounding existing or proposed structures as well as information which would be necessary in the extrapolation of characteristics to future locations.

Involved in this additional work would be the development of test equipment capable of exerting confining pressures up to possibly 40,000 psi in order to obtain information on the deformational moduli at higher pressures. It has been shown in this report that there may be expected only slight changes in the "strength" of the two soils utilized; however, it is still to be determined whether the deformational characteristics will be unchanged.

The techniques of testing, measuring, and calculating used in this program have been continuously upgraded as the program progressed. There are many areas, however, where there is definite need for improvement. One area of interest is with respect to the definition of the length of specimen which is effectively (or freely) deforming. It is apparent from the photographs of the deformed specimens that there is an appreciable end-cap effect on the radial deformation. This suggests the possibility of effects on axial deformations as well. An attempt should be made to determine quantatively the effect of the end cap or to reduce the effect by a redesign of the equipment. Alternatively, it may be feasible to measure axial deformation over a gage length where the end cap effect is negligible. More meaningful results could be obtained if the effective lengt- ...d be more accurately known and utilized in the calculations ...ar and volumetric strain. This would involve the refinement of t... ...ral deformeter as well as refinement of the calculation techniques.

Automated programming of pressure control would be highly desirable in tests of the constant stress ratio and the no-lateral-strain types.

An additional refinement in test instrumentation could be made in the case of axial load measurement. At present, specimen loads are monitored by the use of a load cell mounted externally of the triaxial chamber. Such use makes it necessary to include a "piston friction correction factor" in calculations of stress on the specimen. Although a calibration is made to determine the piston friction, there is some uncertainty with respect to the value and direction of the friction during some portions of the cyclic loading tests. For these reasons, it is highly desirable to use a load cell which measures the load on the specimen directly.

Another area of interest is in regard to effects of handling during specimen preparation and setup on the soil characteristics. Many soil materials are quite sensitive to small changes in water content or to structural changes. Either or both of such changes can occur during the preparation of the specimens for testing. It should be possible to determine, for a given material, the maximum changes in deformational response which could be expected under various preparation conditions. In the case of rock and very stiff soils, this might also include effects of specimen size.

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13. ABSTRACT

This report, Volume I, is concerned with the load-deformation characteristics of two field soils under confining pressures up to 10,000 psi. A wide variety of stress states were imposed upon partially saturated compacted specimens of soil which were obtained from two test sites, one in the United States and the other in Canada. The tests were performed with a high-pressure triaxial cell and the stress states included hydrostatic compression, triaxial shear, constant stress ratio tests, and no-lateral-strain tests. Cyclic loading was accomplished during many of the tests. Results of tests are presented in the form of various types of stress-strain curves in Volume II. Numerical tabulation of data is presented in Volume III. A lateral deformeter was developed for determining lateral deformations of the cylindrical soil specimens during both the compression and the shear stages of loading. The instrument consists basically of strain-gaged, cantilevered springs which bear against the specimen mid-height. The use of the instrument allowed the determination of the bulk modulus of the partially saturated soils as well as the control over the lateral dimensions of the specimens during the loading.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Soil properties						
Soil stresses						
Soil tests						
Triaxial tests						

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